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RECONSTRUCTION OF LATE QUATERNARY ICE-FLOW DIRECTIONS, EAST CENTRAL ELLESMERE ISLAND, N.W.T.

by
Karen Elizabeth Collins

A thesis submitted to the School of Graduate
Studies in partial fulfillment of the requirements
for the degree of M.Sc. in Geology

OTTAWA-CARLETON GEOSCIENCE CENTRE
AND UNIVERSITY OF OTTAWA

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ABSTRACT

This study identifies Late Quaternary glacial ice-flow directions in east-central Ellesmere Island, N.W.T. This was accomplished by the study of till composition and its relation to bedrock sources. The area is well-suited to provenance studies because of the limited areal outcrop of lithologically distinct bedrock. Coarse and fine till fractions were examined at 96 sites, located mostly along a 360 km strip of coastline. At each site, stones (1 to 4 cm in dimensions) were identified within a 60 x 60 cm area on the surface of the till. Granulometric, geochemical, and Munsell colour analyses were performed on the fine fractions. The till was found to have a high sand content throughout the study area and, therefore, granulometry was not useful in identifying paleoflow directions. Similarily, the geochemical composition of the till was too homogeneous to determine provenance. The majority of the tills fell into one of three Munsell colour groups which could be related to the bedrock. Stone count data supplied the best information on former glacial ice-flow. Samples were assigned to five till types, each being an identifiable combination of four different components.

The spatial distribution of the five till types suggests a hypothesis which attempts to reconcile the Innuitian Ice Sheet model of Blake with the Franklin Ice Complex model of England. Glaciers draining from ice sheets in northern Ellesmere Island and Greenland filled Kane Basin and flowed southward toward Smith Sound. The enormous amount of ice resulting from the convergence of these ice sheets was able to deflect southeastward-flowing ice entering Kane Basin (100 km wide) in the Buchanan Bay area. When this southward-flowing ice reached the bottleneck at Smith Sound (40 km wide), it overrode the adjacent landmasses of Pim Island and Cape Herschel and forced Buchanan Bay ice southward through the channel that is now occupied by Rice Strait. The great depth of Smith Sound (500 m) indicates that it, too, was eroded by the southward flow of ice. Southward-flowing ice continued to drain towards Baffin Bay, overriding the coastal areas of Nares Strait at Wade Point and Cape Isabella. The results presented here partially support the Innuitian ice sheet hypothesis, but do not negate the Franklin Ice Complex model. However, the timing of these events remains unclear.

RESUME

Le but de cette étude a été d'identifier les directions des flux glaciaires du Quaternaire récent au centre-est de l'Ile Ellesmere, N.W.T. Ceci a été realisé grâce à l'étude de la composition du till et de sa relation avec la roche mère d'origine. L'aire géographique d'investigation était propice à l'utilisation de la méthode des 'provenance studies', les roches-mères de natures différentes affleurant en des zones bien délimitées. Les fractions de till, fine et grossière, ont été examinées sur 96 sites localisés, pour la plupart, sur un rivage de 360 km de long. Pour chaque site, des galets (1 à 4 cm) ont été identifiés dans une zone circonscrite par un carré de 60 x 60 cm à la surface du till. Pour les fractions fines, analyses granulométriques, chimiques et tests colorimétriques Munsell ont été éffectués. Sur l'ensemble des sites, le till contient une fraction sableuse elevée. Par conséquent, la granulométrie est inopérante pour identifier les traces des anciens flux. De la même façon, la composition chimique des tills est trop homogène pour pouvoir marquer une quelconque provenance. Dans leur majorité, les couleurs des till appartiennent à un des trois groupes de couleur Munsell, qui pourrait correspondre à la roche mère. En revanche, les données sur les comptages de galets constitue la meilleure information sur les déplacements des glaciers. Les échantillons ont été divisés en cinq groupes, chacun correspondant à une combinaison des quatre différents types de roches en proportions variables.

A partir de la distribution spatiale de ces cinq groupes, on propose l'hypothèse suivante: les glaciers s'écoulant depuis les inlandsis situés au nord de l'Ile Ellesmere et du Groënland, remplissent Kane Basin et se dirigent vers le sud à travers Smith Sound. La masse enorme de glace, resultant de la convergence de ces glaciers, a été capable de détourner les glaciers à flux sud-est pénétrant dans Kane Basin (100 km de large) dans la région de Buchanan Bay. Quand ces flux de glace, rédirigés vers le sud, ont atteint le vérrou de Smith Sound (40 km de large) la glace de Kane Basin submerge alors les masses de terre *adjacentes de Pim Island et Cape Herschel. Ce flux détourne également la glace de Buchanan Bay vers le sud au travers du canal qui est maintenant occupé par Rice Strait. La profondeur importante de Smith Sound (500 m) montre qu'il fut erodé par ce flux de glace allant vers le sud. La glace cheminant vers le sud a continué à se déplacer vers Baffin Bay, en submergeant le domaine des côtes de Nares Strait à Wade Point et Cape Isabella. Les résultats presentés ici confirment l'hypothèse de l'inlandsis Innuitien, toute en ne contredisant pas le modèle du 'Franklin Ice Complex'. Toutefois, la chronologie reste imprécise.*

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ACKNOWLEDGEMENTS

Fieldwork (authorized by field party leader W. Blake, Jr.) was carried out under the auspices of the Geological Survey of Canada, Ottawa. Logistical support for the Cape Herschel Project was provided by the Polar Continental Shelf Project, Energy, Mines and Resources. Granulometry and pre-treatment of the samples for geochemical analyses were performed in the Sedimentology Laboratory (P. Lindsay, Head) of the Geological Survey of Canada. The geochemical analyses were paid for by the Geological Survey of Canada. Professor H. French (Department of Geology, University of Ottawa, Ottawa) is gratefully acknowledged for supervising this thesis write-up. The manuscript was much improved thanks to the comments made by Professors O. Dixon and M. Robin (both of the Department of Geology, University of Ottawa), Professor P. Johnson (Department of Geography, University of Ottawa), and Drs. W. Shilts and F. Agterberg (both of the Geological Survey of Canada). Dr. J-P. Lautridrou (Directeur) kindly allowed the use of the facilities of the Centre de Géomorphologie (Centre National du Recherche Scientifique, Caen, France) in 1991-1992 for data analysis and manipulation. Special thanks go to Drs. E. Verrecchia and J-L. Dumont, also to G. Guillemet, M. Joly, and M. Lavollé (all at the Centre de Géomorphologie).

1. INTRODUCTION

1.1 Aims and Objectives

This study improves the knowledge of Late Quaternary ice flow directions in east-central Ellesmere Island by establishing drift composition and its relation to bedrock. The region is well-suited to till provenance studies because Arctic platform sedimentary rocks in the north provide indicator erratics which have distinctive lithologic characteristics and well-defined bedrock sources (Plate. 1.1). The area is of particular interest since the flow direction of present-day outlet glaciers is orthogonal to the inferred former southward direction of ice flow, as indicated by striae and glacially streamlined landforms in the Pim Island - Cape Herschel area (Plate 1.2).

Based on the former flow directions in the study area, the glacial history of east-central Ellesmere Island can be put into a regional context. To achieve this, two questions are addressed. First, do the results of the provenance study indicate a build-up of only local ice on Ellesmere Island in accordance with the Franklin Ice Complex model, as proposed by England (1976b)? Or, are they the result of more expansive glacier ice, caused by the coalescence of the Greenland and Ellesmere Island ice sheets, according to the Innuitian Ice Sheet hypothesis (Blake, 1977)? Second, are the till and associated glacial features related to the last glaciation (Wisconsinan) or are they much older (pre-Wisconsinan)?

The topography of Ellesmere Island and its proximity to Greenland in the Cape Herschel - Pim Island area make it an ideal location for investigation of the past interactions of their respective ice sheets. Along the length of Nares Strait, Ellesmere Island and Greenland are separated in places by a mere 40 to 130 km. Both Ellesmere Island and Greenland presently support major upland icefields which reach maximum elevations of over 2000 m a.s.l.. It is apparent that these icefields served as primary ice dispersal centers during the Quaternary.

Plate 1.1 Light-coloured Arctic Platform erratics make a striking visual contrast with the red Archean granite bedrock on the Cape Herschel plateau.

Plate 1.2 Striations on a small roche moutonnée indicate former glacial flow from north to south across Pim Island. In the background, Leffert Glacier flows eastward into Rosse Bay.

This study contributes to the continuing debate concerning the character and extent of the last glaciation of Ellesmere Island. The latter is critical to any assessment of the paleoclimatic and chronostratigraphic interpretations of high latitude ice cores. The identification of past ice margins is also important in the delimitation of Pleistocene refugia.

1.2 Study Area

Fieldwork was carried out in a coastal ice-free zone of east-central Ellesmere Island (Fig. 1.1). The Cape Herschel station of the 'North Water Project', established in 1973 by the late F. Müller (Müller *et al.*, 1975), was used. Detailed investigations were made in the vicinity of Cape Herschel, on the eastern tip of Johan Peninsula and on Pim Island. Observations were also made on Brevoort Island, on Thorvald, Bache and Knud peninsulas, and as far south as Cadagon Inlet.

The ice-free zone under study covers an area of approximately 75 x 105 km^2. The center of the area is at 78° 35'N, 75° 40'W, approximately 655 km northeast of Resolute Bay, and 280 km east-southeast of Eureka. Access to the field area was by chartered aircraft from Resolute. The rough nature of the terrain frequently necessitated landings by Twin Otter on the sea ice of Rosse Bay, adjacent to the Cape Herschel peninsula, or on a landing strip at Alexandra Fiord, approximately 40 km to the northwest.

1.3 Previous Geological Investigation

Schei was the first geologist to describe the unglaciated parts of east-central Ellesmere Island during the Second Norwegian Expedition in the 'Fram' (1898-1902; Schei, 1903). A comparison of bedrock on Bache Peninsula and northwest Greenland was made by Bentham (1936, p. 427) during the Oxford University Ellesmere Land Expedition and Troelsen during the Danish Thule and Ellesmere Land Expedition (1939-41). Troelsen (1950) applied several Greenland formational names to the Lower Paleozoic succession of Bache Peninsula.

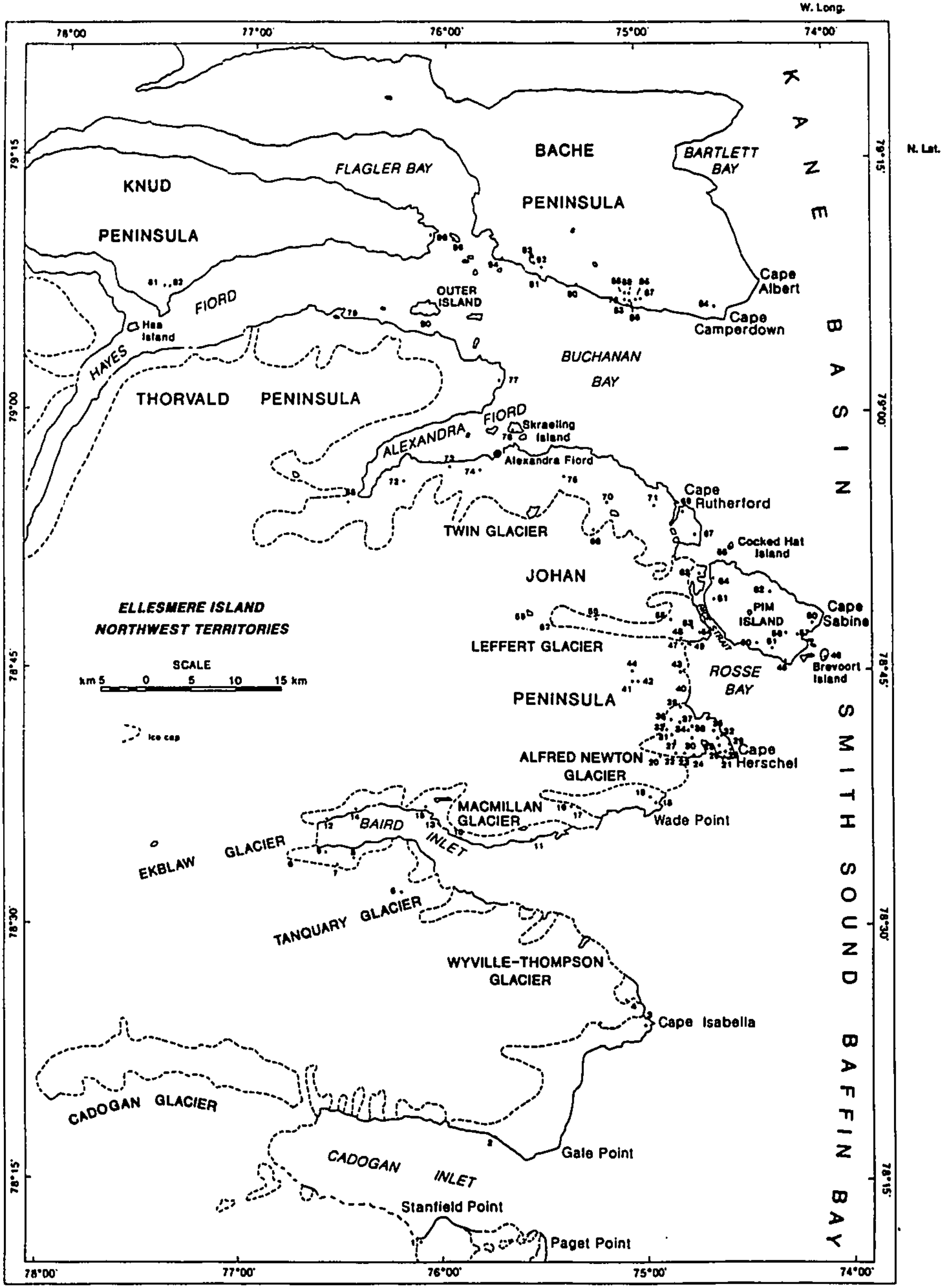

Figure 1.1 Map of the study area showing sample sites.

Stratigraphic relationships described by Schei and Bentham of some basal beds at Bache Peninsula were re-examined by Wordie (1938). Poulsen discussed the relationship between the stratigraphy of Bache Peninsula and northwest Greenland based on identification of Cambro-Ordovician fossils, also collected by both Bentham and Schei (Poulsen, 1946, p. 299).

Investigation of the east coast of Ellesmere Island by the Geological Survey of Canada began in 1954 when Fortier *et al.* defined most major geologic subdivisions. More detailed descriptions of the stratigraphic framework and the prominent features of the region were made by Thorsteinsson and Tozer (1957, 1960). Christie (1962) produced a geological map of east-central Ellesmere Island on a scale of 1:253,440. He later published a more detailed report on Bache Peninsula that included a geological map at a scale of 1:126,720 (Christie, 1967).

Airborne reconnaissance mapping of the Precambrian Shield on Ellesmere and Coburg islands was made by Frisch *et al.* (1978) at a scale of 1:250,000. The Precambrian Shield of Ellesmere, Devon and Coburg islands was the subject of a map at a scale of 1:750,000 and a report (Frisch, 1983), later contained in three maps at a scale of 1:250,000 and a memoir (Frisch, 1988).

A report on the Proterozoic and Cambrian stratigraphy of eastern and central Ellesmere Island was made by Kerr (1967). A volume dealing with geological and geophysical considerations of the landmasses adjacent to Nares Strait (Dawes and Kerr, eds., 1982a) contains several articles correlating the stratigraphy of Ellesmere Island and Greenland. Stratigraphy of the Proterozoic Thule Group, which outcrops in the southern part of the study area has been described by Frisch and Christie (1982) and by Jackson (1986), who also described the same formations on southwest Greenland. Most recently, Trettin (1991) has compiled the geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland.

1.4 Stratigraphy

1.4.1 Introduction

Archean crystalline basement rocks, exposed in the lower nine-tenths of the study area, mark the northern limit of the Canadian Shield (Fig. 1.2). The Archean rocks are unconformably overlain by gently-dipping Proterozoic to lower Paleozoic strata which outcrop in the northern one-tenth of the study area (Plate 1.3). The overlying sequence of relatively undeformed shelf-type Paleozoic sedimentary rocks forms the northeasternmost part of the Arctic Lowlands. To the north and northwest of Bache Peninsula lies the Franklinian geosyncline, characterized in this region by thickened formations, folds, and major thrust faults. Mesozoic/Cenozoic sedimentary strata unconformably overlie the Paleozoic rocks, preserved in down-faulted blocks. A map of the general geology of the area is shown in Figure 1.3.

1.4.2 Late Archean

Archean basement rocks outcrop extensively in the coastal ice-free parts of the study area. These highly deformed granulite facies rocks, part of the Alexandra subprovince of the Churchill Structural Province (Stockwell, 1982), form interleaved northerly-trending belts on Ellesmere Island. Frisch (1988) identified the following rock units: i) orthopyroxene-bearing tonalitic and granitic gneiss; ii) orthopyroxene tonalite, massive to weakly gneissic, commonly veined by granite and pegmatite; iii) orthopyroxene granite, massive to weakly gneissic, commonly perthite-porphyroblastic and veined by granite and pegmatite; and iv) anatectic peraluminous granite with garnet, cordierite and/or sillimanite.

Numerous outcrops of each rock type are scattered throughout the study area, in addition to a dozen small outcrops which have been mapped simply as undifferentiated crystalline basement rocks.

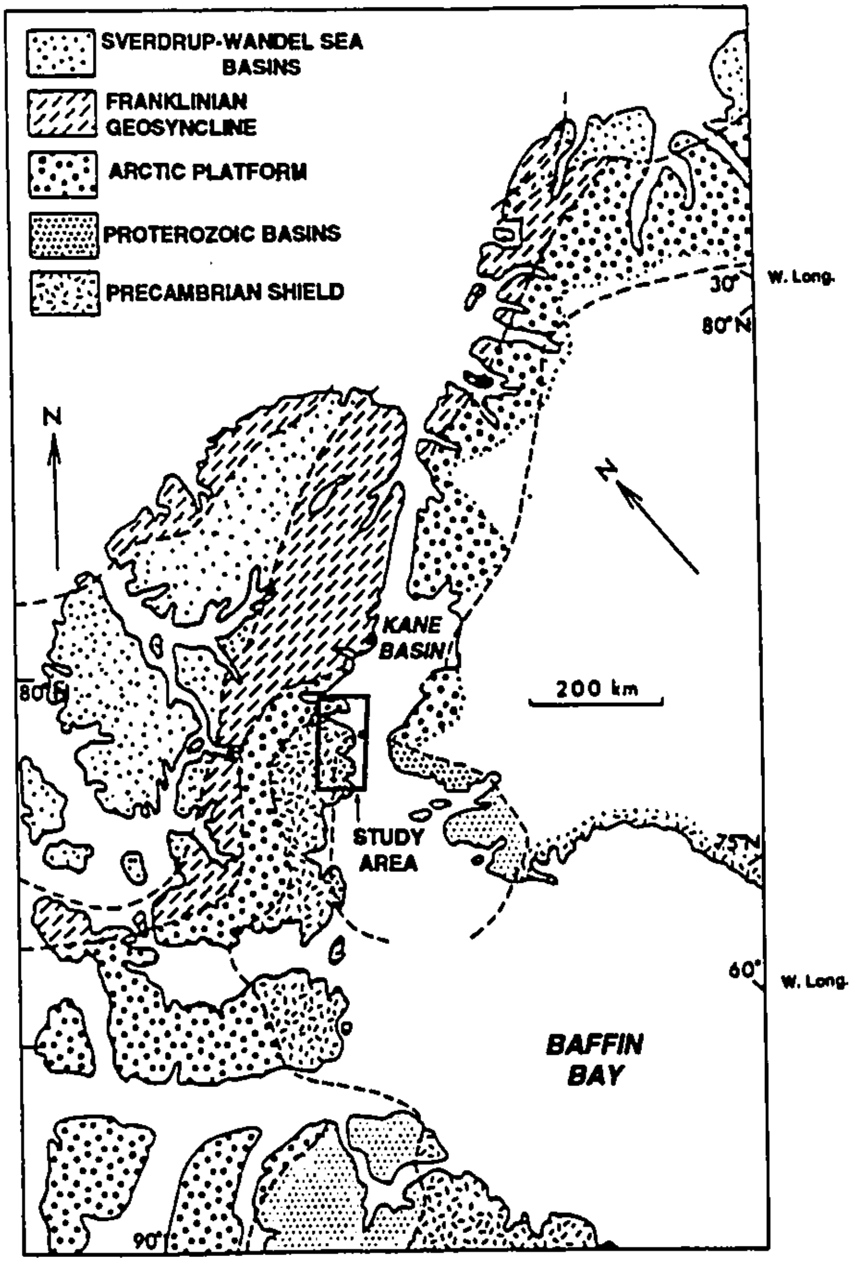

Figure 1.2 Map showing main geological provinces of the eastern Canadian Arctic and North Greenland (Dawes and Kerr, 1982b)..

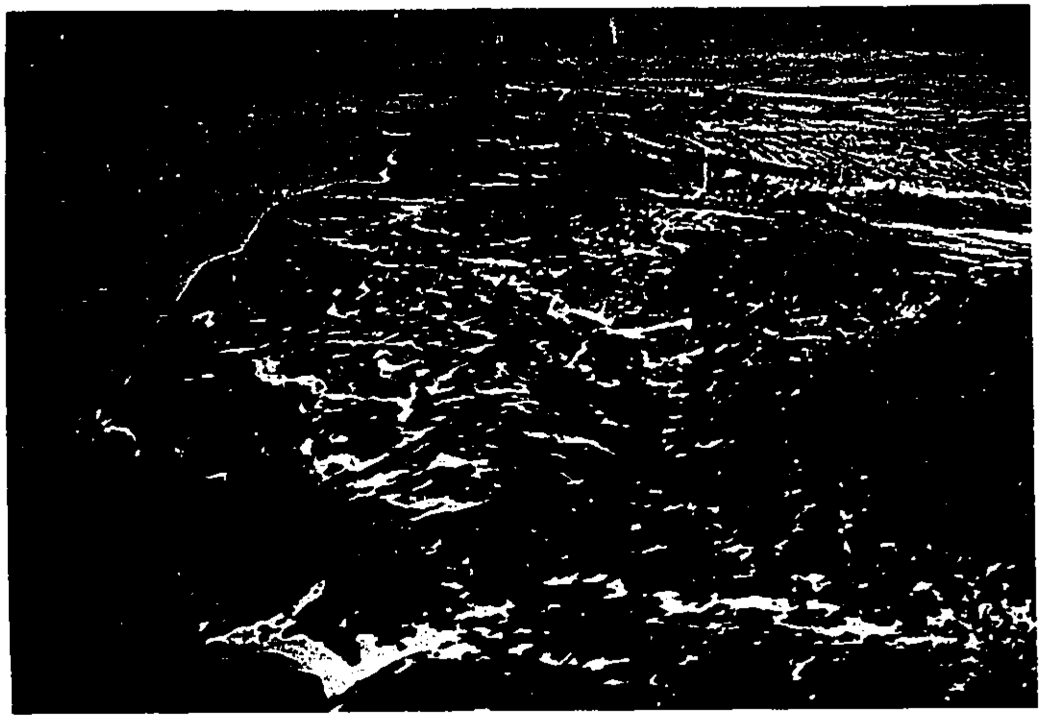

Plate 1.3 View of Bache Peninsula looking west into Hayes Fiord. Precambrian Shield rocks, which outcrop extensively in the southern part of the study area, are overlain by Arctic Platform sediments (right).

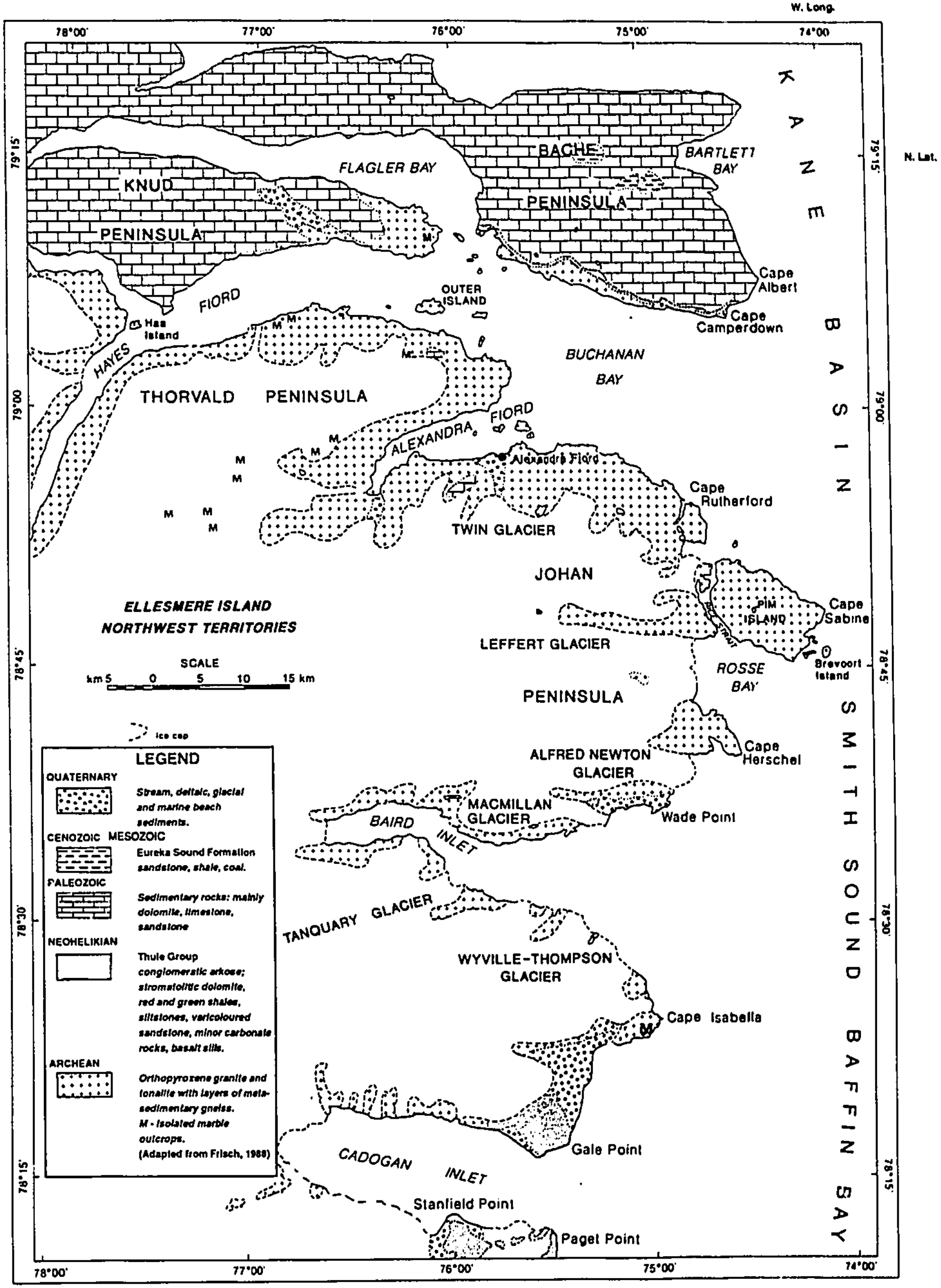

Figure 1.3 Bedrock geology of the study area (adapted from Frisch, 1988).

Marble is the only Archean rock type that is limited in outcrop extent. Small areas of marble bedrock outcrop on the tip of Knud Peninsula, on the northern coast of Thorvald Peninsula, at Cape Isabella, and on numerous nunataks west of Alexandra Fiord.

1.4.3 Neohelikian

The crystalline rocks are overlain by unmetamorphosed sediments and basalts of the Neohelikian Thule Group, which outcrop in three parts of the study area (described in detail by Frisch and Christie; 1982; Dawes *et al.*, 1982a; Jackson, 1986). Frisch (1988) divides the group into three units. The lower unit comprises quartzose sandstone and conglomerate, stromatolitic dolomite, and varicoloured shale and siltstone of shallow marine to continental origin. Tholeiitic basalt sills and volcanic breccia are interbedded with these sediments. The middle unit consists almost entirely of sedimentary rocks, chiefly red and green shale, siltstone, sandstone and orthoquartzite. Basalt sills and calcareous rocks are minor components. These two lower units outcrop on the south side of Cadogan Inlet and 8 km west of Wade Point, between MacMillan and Alfred-Newton glaciers.

The third unit of the Thule Group consists of unmetamorphosed clastics and basalts of the Camperdown Member which is the only member of the redefined Rensselaer Bay Formation (Peel *et al.*, 1982; Table 1.1). The Rensselaer Bay Formation was originally defined by Troelsen (1950) as being composed of the lower Camperdown Member, the middle Bache Peninsula Member, and the upper Sverdrup Member. Troelsen thought these to be Cambrian in age, although later, Christie (1967) did not exclude the possibility that the lower part of the formation was Proterozoic. Dolerite sills of the Rensselaer Bay Formation in Inglefield Land, Greenland subsequently yielded $^{40}K/^{40}Ar$ ages in the range 1070 +/- 40 m.y. to 1190 +/- 40 m.y. (Dawes *et al.*, 1973; Dawes *et al.*, 1982b). Underlying crystalline basement rocks have been dated as young as 1520 m.y. (Larsen and Dawes, 1974), implying

AGE	FORMATION	BACHE PENINSULA	INGLEFIELD LAND
EARLY PALEOZOIC	Dallas Bugt	Sverdrup Member	Marshall Bugt Member
			Qaqaitsut Member
		Bache Peninsula Member	Kap Scott Member
NEOHELIKIAN	Rensselaer Bay	Camperdown Member	(not formally subdivided)

Table 1.1 Neohelikian and earliest Paleozoic stratigraphy of Bache Peninsula, Ellesmere Island and Inglefield Land, Greenland (adapted from Peel *et al.*, 1982).

that the Rensselaer Bay Formation is of late Proterozoic (Helikian) age. The lower of two dolerite sills intruding the Camperdown Member on Bache Peninsula was found by K/Ar dating to be 1197 +/- 33 m.y. old. Thus, the Camperdown Member was acknowledged to be the sole member of the redefined Proterozoic Rensselaer Bay Formation (Peel *et al.*, 1982).

The Rensselaer Bay Formation unit outcrops for 45 km along the southern cliffs of Bache Peninsula, thinning westward from a maximum thickness of about 85 m at Cape Camperdown until it pinches out in the vicinity of Koldewey Point at the mouth of Flagler Bay (Christie, 1967). Christie (1983) noted that the Rensselaer Bay Formation must also form submarine outcrops in southwestern Kane Basin which may now be mantled by glacial and marine deposits. The two basaltic extrusive and hypabyssal rock units alternating with red beds increase the thickness of this member to approximately 140 m (Peel *et al.*, 1982).

Christie (1967) identified four sub-members of the Camperdown Member near Cape Camperdown, summarized here in descending order : i) thin- to medium-bedded white to purple sandstone; up to 33 m in thickness; ii) interbedded, thin-bedded, fine-grained, red-weathering sandstone, sandy shale, and shale with abundant mud-cracks and ripple-marks; approximately 33 m thick; ii) medium-to fine-grained, medium-bedded sandstone, greenish to white in colour, with some crossbedding; 9 to 22 m thick; and iv) a basal, impure thin-bedded sandstone unit with shaly green and red parting; 3 m thick.

1.4.4 Paleozoic and Younger

The middle and upper units originally assigned to the Rensselear Bay Formation, the Bache Peninsula and Sverdrup members, were subsequently assigned to a new early Cambrian formation called 'Dallas Bugt' (Peel *et al.*, 1982, p. 108) which attains a thickness of about 60 m at Bache Peninsula. The Bache Peninsula Member, a coarse-grained, thick-bedded, dark purple-brown conglomeratic arkose, overlies the Rensselaer Bay Formation. It outcrops to the same lateral extent as the Rensselaer Bay Formation, and has a maximum measured thickness of 9 m, and thins rapidly to the west (Christie, 1967; Plate 1.4). Pebbles (up to 10 cm in diameter) in the conglomerate include black chert, jasper and abundant brown-weathering, well-rounded quartzite. Angular sandstone boulders up to 20 cm in diameter are also present. The Bache Peninsula Member is considered to be equivalent to the Kap Scott Member of Inglefield Land (Peel *et al.*, 1982).

The overlying lower Paleozoic strata, with the Sverdrup Member of the Dallas Bugt Formation at the base, outcrop extensively in the Flagler Bay region. They are exposed over much of Bache Peninsula and most of Knud Peninsula, the strata dipping gently to the north. Scattered outliers of these rocks occur on Thorvald Peninsula and on the south side of Alexandra Fiord. The Sverdrup Member is a medium- to coarse-grained quartz sandstone. It is characteristically cross-bedded and contains pebble-conglomerate layers with quartz pebbles up to approximately 5 mm in diameter. In places, the white to pale yellow sandstone is characterized by regular, sub-columnar tubes or pipes, probably referable to *Skolithos* (Peel *et al.*, 1982). A gradation from arkose to quartz sandstone is apparent on weathered surfaces by a distinct purple and white banding in the Sverdrup Member. On fresh surfaces the rock is always uniformly white and weathers white, pale yellow or pale purple. The Sverdrup Member increases to a thickness of 95 m in the west and rests directly on crystalline basement in the vicinity of Sverdrup Pass (Peel *et al.*, 1982). The Sverdrup Member is correlated principally with the Qaqaitsut Member, Inglefield Land, but a fine-grained greenish sandstone at the top of the Sverdrup Member (Christie, 1967) is probably a correlative of the Marshall Bugt Member (Peel *et al.*, 1982, p. 111). The overlying Lower Cambrian to Middle Ordovician rocks are mostly grey or light-coloured clastics and carbonates. Many of the formations are fossiliferous and have been described by Christie (1967).

The Upper Cretaceous/Tertiary Eureka Sound Formation has very limited distribution, outcropping in only one small area of eastern Bache Peninsula. Included in this formation

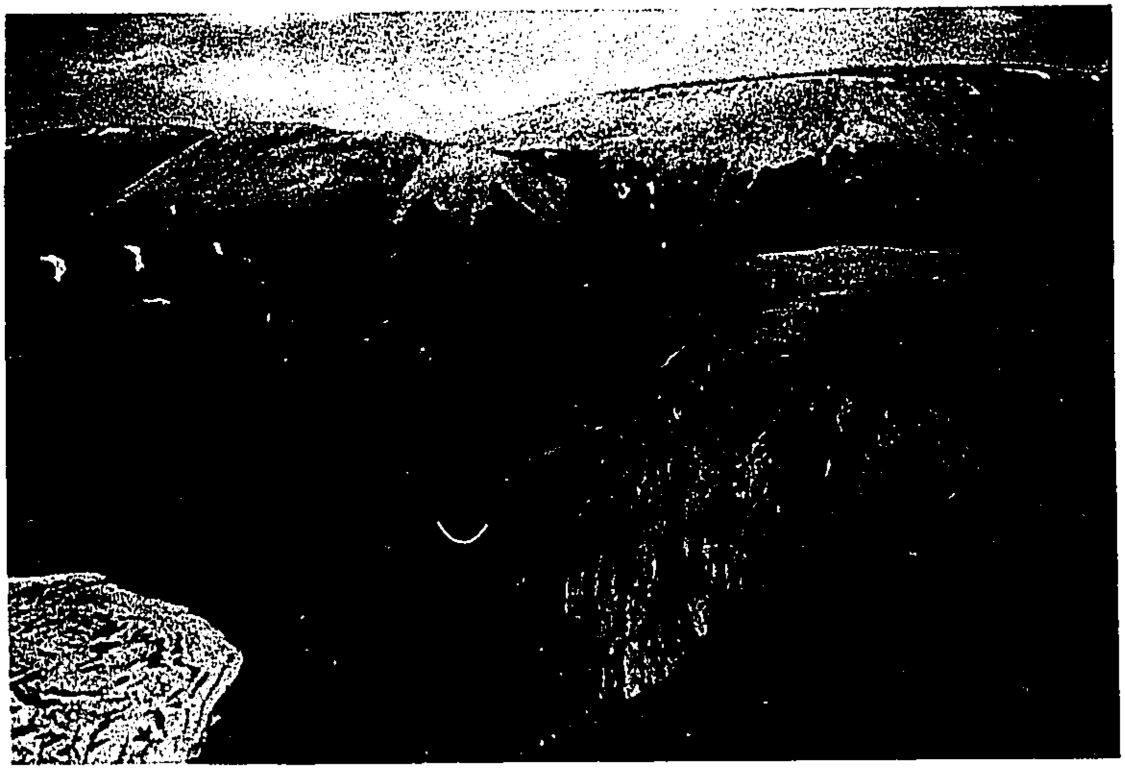

Plate 1.4 Green and dark purple talus slopes indicate outcrops of the Rensselaer Bay Formation and the Bache Peninsula Member. Light-coloured Paleozoic rocks overlie these units.

are quartz and carbonate sandstone, conglomerate, shale and coal. The sandstones are medium-grained, light brown or yellowish white-weathering rocks. The conglomerate consists of well-rounded carbonate pebbles 2 to 10 cm in diameter in a sand matrix. Poorly consolidated green-grey and grey-brown shaly sandstone and shaly coal (lignitic) lenses and seams complete this formation which has a thickness of approximately 250 m.

1.5 Physiography and Late Quaternary Glacial History

1.5.1 General

Today, northern Ellesmere Island is a polar desert with annual precipitation ranging from 2.5 cm/year in its continental interior to about 15 cm/year on the highland ice caps and along the more maritime coasts (Jackson, 1959; Hattersley-Smith, 1963). Despite this aridity, northern Ellesmere Island supports extensive icefields more than 1,000 m a.s.l. (Fig. 1.4). The United States Range in the north and the Agassiz Ice Cap in the south each cover approximately 17,000 km^2. A major center of ice dispersal exists over the United States Range where piedmont glaciers descend southward along the northern edge of the Hazen Plateau. The landscapes along the bordering coastlines of both Greenland and Ellesmere islands are characterized by dissected plateaus and mountains of low to moderate elevation (300 to 1,200 m a.s.l.). From a physiographic viewpoint, therefore, this region represents a relatively open area for the former interaction of the Ellesmere Island and Greenland ice sheets.

Much of the Prince of Wales Icefield (see Fig. 1.4) is underlain by mountainous terrain, as evidenced by numerous nunataks rising to 2,350 m a.s.l. From the coast, long fiords penetrate the interior and separate relatively low plateaus on Bache, Knud, Thorvald and Johan peninsulas, which themselves are bounded by steep slopes or sea cliffs. Lateral moraines, some several kilometres in length, are perched along the steep-walled fiords (Plate 1.5). Former deltas are common features in the inner parts of the fiords and raised coastal

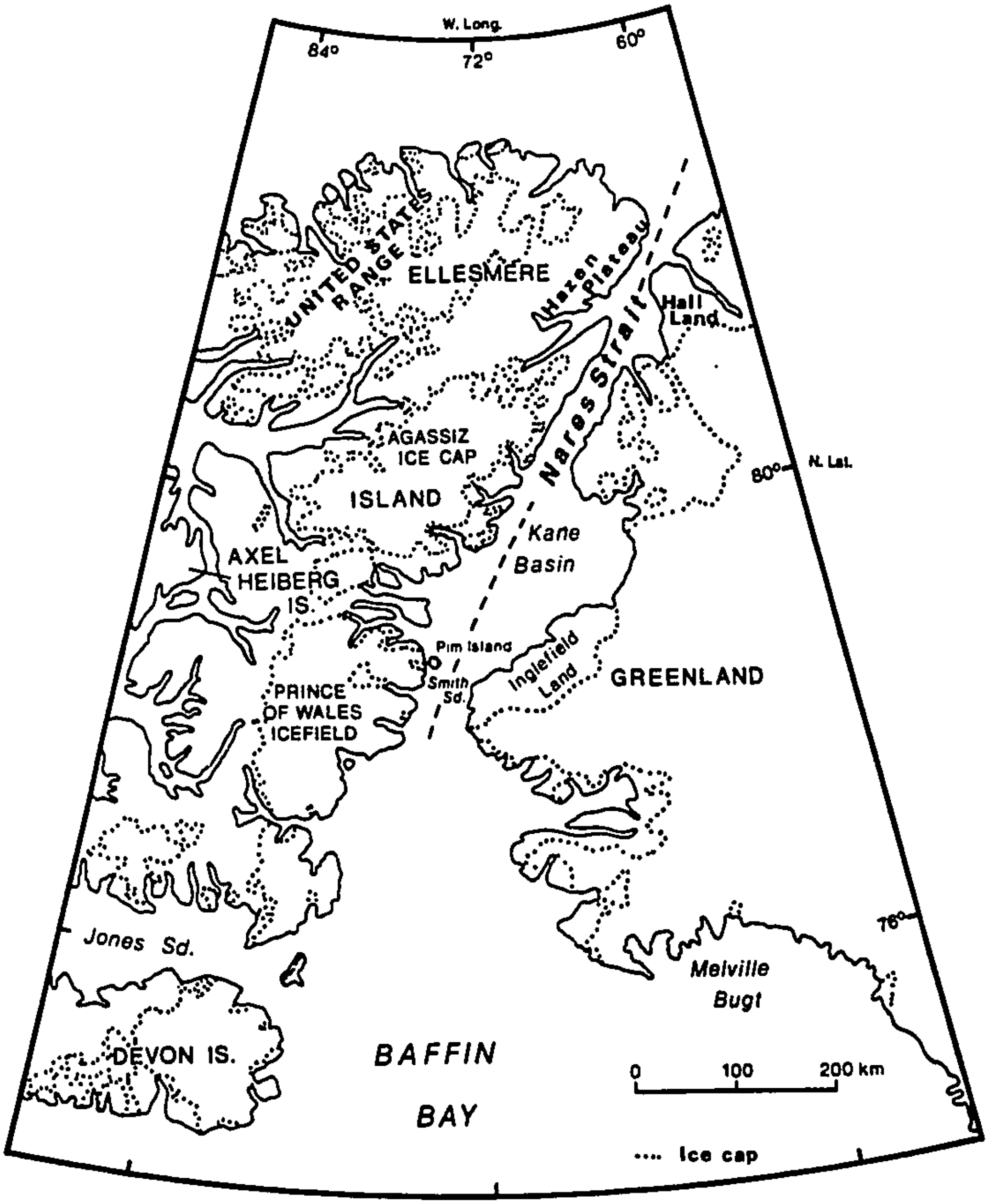

Figure 1.4 Map of Ellesmere Island and northwestern Greenland (adapted from Blake, 1989).

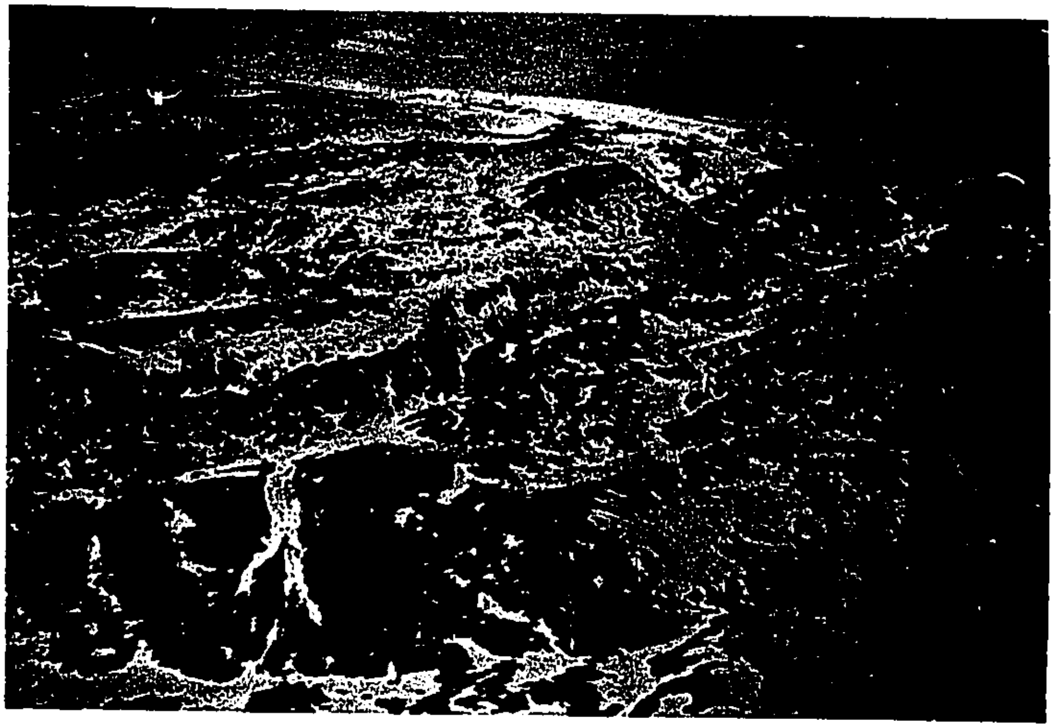

Plate 1.5 Linear features accentuated by the snow are lateral moraines parallel to the length of Alexandra Fiord.

deltas are present along Smith Sound. One such delta can be found on the southwest side of the Cape Herschel peninsula (Plate 1.6). Numerous former marginal drainage channels, many 10 to 30 m deep, are striking glacial features which, in places, dissect the plateaus of Bache, Knud, Thorvald and Johan peninsulas, terminating along the walls of the fiords. U-shaped and hanging valleys are other large scale erosional features which are evidence of more extensive glaciation.

Today, the Prince of Wales Icefield and several smaller plateau ice caps cover most of the region to the west and south of the study area. East-central Ellesmere Island is characterized by tidewater glaciers along approximately 30% of its coastline (Koerner, 1979). These presently flow eastward toward Smith Sound. There is evidence that many of these glaciers have advanced in recent years. For example, in 1861, Hayes described a plain 6 km wide between a glacier and the sea at Gale Point, at the northern entrance to Cadogan Inlet (Hayes 1867, p. 424-425). Fifty-six years later, MacMillan (1928, p. 379) found no plain but a glacier reaching out into the sea.

The possibility that east-central Ellesmere Island was glaciated beyond its present extent was first considered by Schei in 1903, who erroneously concluded that the existing glaciation represented a maximum. Schei stated, "I nowhere observed roches moutonnées, neither did I observe striae or scouring. Nay further, I did not perceive any loose materials that could with any degree of likelihood be ascribed to the effects of glacier ice" (Schei, 1903, p. 64). However, Schei did note the elevation of several marine terraces near the winter-quarters of the 'Fram' (1898-99), in Rice Strait and at nearby Cape Rutherford. Details of these marine terraces as well as the identity of marine mollusca collected on the north side of Pim Island were published by Holtedahl (1917) in a summary of Schei's geological results. Photographs taken during the 'Fram' expedition convinced Holtedahl that Schei had overlooked evidence of more extensive glacial erosion (Holtedahl, 1917, p. 21).

Plate 1.6 A former delta (indicated by the arrow) near Cape Herschel Peninsula, west of Elison Pass.

Troelsen (1952) observed widespread evidence of glaciation on Ellesmere Island and Craig and Fyles (1960) considered the possibility that the island was completely ice-covered during the last glaciation. Fyles (in Jenness, 1962, p.5) published the first report on the Quaternary geology of western Ellesmere Island. His observation of freshly glaciated rock surfaces bordering some fiords in close proximity to bedrock rubble in the uplands led him to suggest that a late Pleistocene glaciation covered only part of the region and that complete glaciation took place much earlier. Similar conclusions were made by both Boesch (1963) and Hattersley-Smith (1969), who studied glacial features adjacent to an ice cap in central Axel Heiberg Island and at the head of Tanquary Fiord, northern Ellesmere Island, respectively. Ice-marginal landforms marking former standing or readvancing ice fronts on west-central Ellesmere Island have been studied by Fyles (see Jenness, 1962; Craig and Fyles, 1965) and Hodgson (1973, 1985).

The Quaternary sediments of east-central Ellesmere Island were not investigated until 1961, when Christie noted various glacial deposits and included these observations in a report of Bache Peninsula (Christie, 1967). He commented on both the composition and provenance of the till and identified beach deposits, some of which contained marine pelecypod shells. Christie suggested that the local limit of postglacial marine submergence was between 60 and 110 m a.s.l.

Although there is considerable evidence throughout the Queen Elizabeth Islands for more widespread glaciation during the Quaternary, the character and extent of this glaciation has yet to be resolved. One theory is that the Queen Elizabeth Islands and the inter-island channels were continuously covered by a pan-archipelago ice sheet (Blake, 1970, 1972, 1976). However, there is also evidence to support a more restricted glaciation in which a convergent but not necessarily coalescent system of icefields existed (England 1976a, 1976b, 1978, 1983, England *et al.*, 1981). The most important evidence for these two models (called the Innuitian Ice Sheet and the Franklin Ice Complex, respectively) is summarized below, with particular attention given to arguments concerning the study area. (See Fig. 1.4 for locations discussed in the text.)

1.5.2 Innuitian Ice Sheet Model

The eastern and central Queen Elizabeth Islands presently support major upland icefields which reach maximum elevations of over 2,000 m a.s.l.. Blake (1977) proposed that these icefields expanded during the last glaciation to form a large contiguous ice sheet over the Queen Elizabeth Islands. Presumably, this contiguous ice mass also coalesced with the Laurentide Ice Sheet in Lancaster Sound to the south. North of the study area, the Humbolt Glacier draining the Greenland Ice Sheet and numerous valley glaciers issuing from northern and central Ellesmere Island are thought to have coalesced to form a ridge 700 to 800 km wide, centered over Kane Basin. The glacio-isostatic, paleoclimatic and other evidence for the Innuitian Ice Sheet model is discussed below.

The amount of postglacial emergence is commonly thought to reflect the magnitude of a former ice load. Thus, regional isobases drawn on postglacial shorelines are commonly used to infer the pattern of ice cover. Shoreline emergence studies in southwest Ellesmere Island show that the 6500- and 5000-year-old strandlines in Jones Sound tilt to the northwest (Blake, 1970). The maximum elevation of the 5000-year-old strandline can be found in a broad zone running northeast-southwest between Bathurst Island and Eureka Sound. This is considered to coincide with the greatest thickness of the Innuitian Ice Sheet. This center was then extended northeastward from Eureka Sound, across north-central Ellesmere Island to northern Greenland (Walcott, 1972; Andrews, 1973). In addition, the age of the highest finite-dated marine shells decreases from the western islands towards Ellesmere Island suggesting that melt and break-up of the ice sheet and subsequent invasion of marine waters advanced across the Arctic islands from east to west. The initial postglacial emergence and the subsequent entry of driftwood into the inter-island channels and fiords is thought to have occurred between 9,000 and 8,000 years BP (Blake, 1972, 1974).

Another approach applied to the dating of glacial events has been the age determination of organic deposits associated with till or outwash (Blake, 1981, 1982, 1987, 1989). Radiocarbon dating of the basal increment from lake sediment cores or peat deposits provides a minimum age for deglaciation and for the onset of organic accumulation by indicating the time of change from marine to lacustrine conditions. To date, no organic lake sediments have been obtained from either east-central Ellesmere Island or northwestern Greenland, which span more than Holocene time. Blake argues that if any of these sites were free of glacier ice throughout Late Wisconsinan time, then a longer record of continuous organic sedimentation should be present. The fact that older organic deposits have not been found suggests that a cover of glacier ice was present until immediate pre-Holocene time.

Erratics, striae and sculpture also indicate that Ellesmere Island was more extensively glaciated at some time in the past. High-elevation erratics, meltwater channels, and striae reported at 600 to 1000 m a.s.l. from various parts of Ellesmere Island suggest that glaciers once filled the fiords and overtopped intervening highlands (Christie, 1967; Hattersley-Smith, 1969; Blake, 1977; England 1978; England and Bradley, 1978; England *et al.*, 1981; Hodgson, 1985). In the study area, 'fresh-looking' glacial structures and erratics more than 500 m a.s.l. have been interpreted as evidence for expansive, non-local ice of late Wisconsinan age flowing southward from Kane Basin through Smith Sound (Blake, 1977). Glacially-sculptured features on the plateau of Pim Island (550 m a.s.l.) such as roches moutonnées with highly polished, striated and grooved north sides and plucked south sides, are thought to indicate a north-south direction of glacial flow (Plate 1.7). Likewise, rounded north slopes and steep south-facing cliffs (nearly 200 m high) at Cape Herschel are larger

Plate 1.7 Roches moutonnées on Pim Island showing the classic rounded stoss side and plucked lee side indicate former glacial flow from north to south.

scale features which probably resulted from north-south flow. Striae, grooves and roches moutonnées atop the Cape Herschel plateau also have a north-south orientation. The location of striae plus marble erratics (marble outcrops in the north of the study area) identified by Blake are shown on Figure 1.5.

According to Blake (1977), the volume of ice flowing southward from Kane Basin (100 km across and for the most part less than 200 m deep) was sufficient to override adjacent landmasses upon reaching the bottleneck at Smith Sound (40 km across and with a maximum depth of over 500 m). The force of this outlet glacier moving southward was capable of deflecting eastward-flowing glaciers entering Smith Sound in the Buchanan Bay area of Ellesmere Island. These outlet glaciers were deflected so that they flowed southward through Rice Strait, across Pim Island and south-southwestward across Cape Herschel.

This hypothesis is supported by erratic collections made by Christie (1983) in the Pim Island - Cape Herschel area, from which he identified two suites of rocks - the 'Inland Suite' and the 'Cape Suite'. The Inland Suite comprises lower Paleozoic rocks; it was identified at sites on southern Knud Peninsula, northern Thorvald Peninsula, west-central Pim Island, on the west side of Rice Strait, and in a lateral moraine on the north side of Leffert Glacier nunatak. The Cape Suite erratics include Rensselaer Bay Formation rocks in addition to the younger Paleozoic sedimentary rocks of the Inland Suite. Three of Christie's seven collections, made at sites on east-central Pim Island, Brevoort Island, and on the top of Cape Herschel Peninsula contain Rensselaer Bay Formation rocks as erratics. From the limited amount of data collected, Christie (1983) suggested that Pim Island may have acted as a barrier behind which Kane Basin ice pushed westward at some time.

The idea of a major stream of ice flowing southward out of Kane Basin is also supported by analysis of till samples collected from the Cape Herschel plateau. Richardson (1989) made a comparison of three grain size fractions: >30 cm, <30 cm and >3 cm, and <2 mm. The intermediate grain size contained 29% by weight clasts of sedimentary origin as

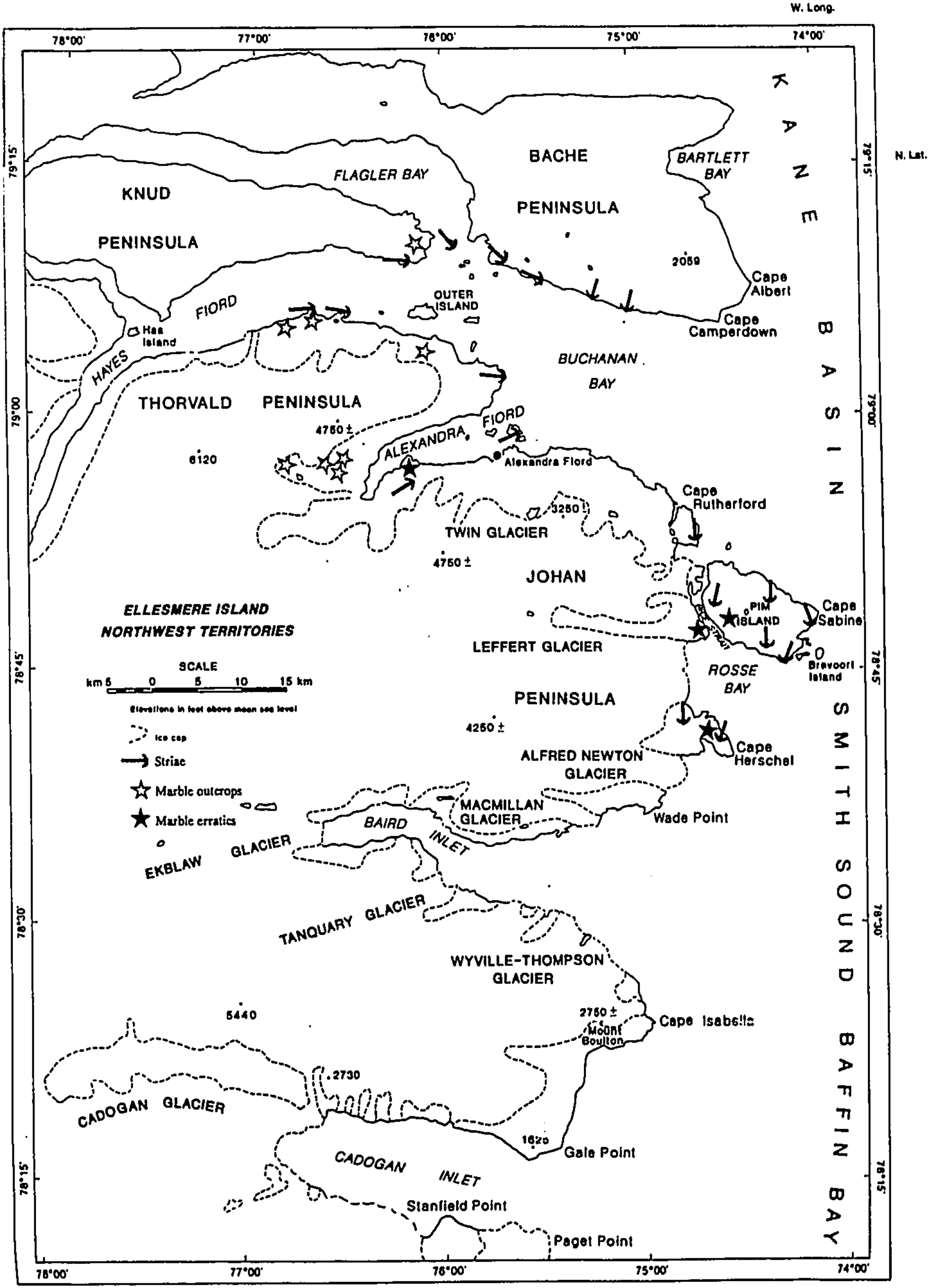

Figure 1.5 Orientation of glacial striae, position of marble outcrops and marble erratics.

opposed to the boulder grain size of which basement and sedimentary rocks accounted for 2% by weight. The finer fraction of till is thought to reflect a longer period of mixing and transport. The sand/silt/clay ratio for the <2 mm fraction was found to be 61.3/25.4/13.3. The high sand component was considered to be consistent with comminution of the numerous soft sandstones that outcrop on Bache Peninsula, 40 km to the northwest. The till, which contained numerous marine shell fragments, was concluded to be a reworked glacio-marine sediment.

The thin veneer of glacial debris covering most of the ice-free terrain in the Cape Herschel - Pim Island area is thought to represent a single till deposited during the same glacial event that produced the striae and glacial sculpture (i.e. the last glaciation that took place in the study area). Thus, Blake (1977) cited the numerous precariously perched boulders, the freshness of the glacial features and the lack of glacial weathering along the contacts between rocks of different grain size as proof that the last glaciation that affected the Pim Island - Cape Herschel area took place relatively recently in geologic time, probably within the last 50,000 years. He argued that if these features were the product of a glaciation during early Wisconsinan time (that is to say, >50,000 years BP), one would expect a deterioration of fine striae, and weathering pits and the absence of unstable-looking perched boulders.

In connection with Blake's work, Watts (1981, 1983) described incipient weathering features on coastal granites in the area and attempted to make an estimate of the age of the fresh-looking glacial features. Detailed examination of grus accumulations, spalled crusts, exfoliated joint blocks, and weathering pits in the lowlands of Alexandra Fiord led him to conclude that they post-dated the last Wisconsinan ice advance. He argued that any subsequent glacier flow out of the fiord would have destroyed the striae and other glacial sculpture in this area.

As a further argument, Blake (1987) noted that the disappearance of massive volumes of ice in immediate pre-Holocene time (based on the lack of older organic lake sediments) is in agreement with the drastic warming documented by the changes in oxygen isotopes from the Camp Century ice core, Greenland (Dansgaard *et al.*, 1984), from the Devon Island Ice Cap cores (Koerner and Fisher, 1985) and from the Agassiz Ice Cap cores, northern Ellesmere Island (Koerner *et al.*, 1987).

1.5.3 Franklin Ice Complex Model

In contrast to the Innuitian Ice Sheet model, England (1983) proposed that the extent of Wisconsinan ice was relatively minor in the High Arctic. He attributed a lack of extensive glaciation to a period of extreme aridity caused by the build-up of the Laurentide Ice Sheet to the south. England based his theory on glacio-isostatic, morphostratigraphic and paleoclimatic data from northeastern Ellesmere Island and northwestern Greenland.

England (1983) has documented the existence of a "full glacial sea" that occupied an ice-free corridor between northeast Ellesmere Island and Greenland during the last glaciation. His use of the term "full glacial sea" includes all areas occupied by the sea during the last glacial maximum, therefore during full glacial conditions. On northeast Ellesmere Island, the Hazen moraine system marks a restricted ice advance out of the United States Range, the terminus of the last glaciation in this area. Deglaciation from the Hazen Moraines began between 7,500 and 8,100 years BP (England, 1974). On Hall Land, northwest Greenland, twenty-seven samples of marine shells from proximal and distal sides of moraines have been radiocarbon dated. Distal to the moraines, the limit of the full glacial sea is dated by *in situ* shells that range from 8,200 to >33,000 years BP. This fauna demonstrates that the sea, rather than the glaciers, occupied most of these fiords thoughout the last glaciation and provides a direct measure of the glacio-isostatic unloading of this area.

Using these data, England (1976b) constructed isobases for the High Arctic at 7,500 and 6,000 years BP. Contrary to Blake's data, they do not indicate an isolated center of uplift over Eureka Sound; they do, however, consistently show a major ridge of uplift extending westward from northwestern Greenland across Kane Basin with gradually declining values towards Eureka Sound. England suggested that the isobases in the eastern Queen Elizabeth Islands had a gradient and orientation that reflected their ultimate dominance by the Greenland Ice Sheet. England argues that ice sheets depress the crust beyond their margins (since the lithosphere is rigid), therefore, Greenland and Ellesmere Island ice did not have to coalesce to produce this emergence pattern (England, 1976a, 1982).

Using these curves, England (1985) calculated that the emergence from the full glacial sea reached 150 m along the last ice limit on Hall Land and 124 m in Clement Markam Inlet. This amount of postglacial emergence is commonly cited as evidence for a former ice sheet over the Queen Elizabeth Islands (Blake, 1970, 1975); however, England demonstrated theoretically that relatively little ice retreat can cause between 140 to 150 m of emergence (England, 1974, 1983, 1986a). His geophysical model reproduces the observed postglacial isobases by assuming a retreat of only ca. 100 km by the Greenland ice sheet and approximately 60 km by the Ellesmere Island ice following the last glaciation. As England pointed out, the geophysical model has limitations; for example, a sparsity of control points (only 2 sites on the entire north coast of Ellesmere Island; England, 1976a) which allows different interpretations of modelling by other authors. England and Bednarski (1986) concluded that Holocene emergence (up to 120 m a.s.l.) on northern Ellesmere Island, caused by the retreat of outlet glaciers by 40 to 100 km, has occurred along coastlines that remained ice-free during the last glaciation. The marine limit is tilted isostatically toward the northwest Greenland Ice Sheet, which dominated postglacial emergence in the peripheral depression.

The limit of this full glacial sea is thought to have modified any weathered till and higher shorelines related to older glaciations. Radiocarbon and amino acid dating of over 25 samples identified a 285 m a.s.l. shoreline (which dates between 500 ka and 1 Ma) and a 175 m a.s.l. shoreline (dated to be greater than 35 ka), which demonstrate that the older and more extensive glaciations produced greater emergence (unloading) than the last glaciation with its local marine limit at 120 m a.s.l. (England, 1987).

England also identified prominent weathering zones along a 70 km section of western Kennedy Channel. The oldest zone is a deeply weathered, erratic-free terrain that extends from the mountain summits down to approximately 470 m a.s.l., providing no evidence of former glaciation. A second zone extends from approximately 470 to 370 m a.s.l. and is characterized by crystalline erratics of Pre-Cambrian provenance deposited more than 80,000 years BP (based on amino acid ratios in shelly till; England and Bradley, 1978). England proposed that this deposit represents the maximum advance of the northwest Greenland Ice Sheet which flowed about 100 km beyond its present margin onto northeast Ellesmere Island (England *et al.*, 1981).

In addition, several deeply weathered till zones, representing multiple glaciations on outermost Inglefield Land, northwest Greenland, have remained undisturbed despite their present-day proximity to the Humbolt Glacier to the north and main Greenland Ice Sheet to the east (Tedrow, 1970). England (England *et al.*, 1981) questioned the likelihood that this low plateau (ca. 200 to 450 m a.s.l.) could have escaped erosion by an expansive Greenland Ice Sheet that severely sculptured more distant and higher portions of east-central Ellesmere Island, thus, involving an ice thickness of at least 1200 m at the entrance to Smith Sound (Blake, 1977). England argued that there is evidence for widespread ice-free areas along northeastern Ellesmere Island and northwestern Greenland during late Wisconsinan time, in addition to at least two older and more extensive glaciations.

England also used paleoclimatic evidence to demonstrate that the Laurentide and Innuitian maxima were not contemporaneous, but that their buildup in time was out of phase. England (1986a) calculated the paleoglaciation level for north-central Ellesmere Island to have dropped by as much as 500 m during the last glaciation. The glaciation level represents the lowest elevation at which ice can persist on a given landscape, which is equal to the mean of the lowest summit with ice and the highest summit without ice. The most important variable affecting the stability of the glaciation level is climatic change. Therefore, the area was characterized by severe continentality, i.e. greater summer cold and severe aridity equal to, or greater than, that of today. This is thought to have produced small, cold-based ice caps on many plateaus that are ice-free today. Also, it would have greatly constrained glaciers, particularly those that entered the sea and calved (England, 1986b, 1987).

Paleoclimatic theories argue for increased aridity and hence reduced ice extent in high latitudes during the last glaciation (Tanner, 1965; Lamb and Woodroffe, 1970; Williams *et al.*, 1974; Boulton 1979). High Arctic aridity has also been suggested from isotope studies of the Camp Century ice core (northern Greenland) and Devon Island ice core records where increased cold (greater continentality) began after approximately 60,000 years BP (Dansgaard *et al.*, 1970). Extreme aridity in high latitudes likely resulted from the buildup of the late Wisconsinan Laurentide Ice Sheet to the south (Lamb and Woodroffe, 1970) coupled with corresponding changes in the atmosphere - ocean circulation in the North Atlantic - Baffin Bay region (Johnson and McClure, 1976). The late Wisconsinan Laurentide Ice Sheet may have acted as a topographic barrier that effectively restricted the advection of moisture from the south into the Arctic archipelago, resulting in diminishing ice bodies to the north. Botanical and zoogeographical studies also support the view of a limited ice cover in the area during the last glaciation as evidenced by Wisconsin-age(?) refugia on northern Ellesmere Island (Brassard [1971] and Leech [1966], respectively).

The numerous deep basins in the sound and fiord systems throughout the Queen Elizabeth Islands have also been cited in support of extensive former glaciation (Blake, 1970). Their origin is thought to have been the channelling of ice streams down pre-glacial valleys or 'selective linear erosion', however, their absolute age remains undetermined. In fact, little erosion is predicted by a theoretical maximum ice cover over the Queen Elizabeth Islands, because much of the ice was cold-based (Sugden, 1978). England (1976b) argued that glacial overdeepening of High Arctic fiords and inter-island channels did not occur beneath isolated outlet glaciers because they would have been thinner and thereby mainly cold-based and protective. He cited an example of a large valley, ideally suited for 'selective linear erosion' by ice, in which an alluvial fan, pre-dating the last glaciation, was altered only slightly (England, 1986b). England pointed out that selective linear erosion has not been demonstrated to take precedence over alternative causes for such valleys, for example, faulting.

The Canadian Arctic islands represent a Tertiary fluvial landscape developed on a contiguous landmass subsequently fractured by block faulting. England contended that if ever there was a regional ice sheet over Arctic Canada, it likely occurred on a prefaulted, contiguous landmass that had a more temperate climate than at present, possibly during the late Tertiary (England, 1987). After block faulting, the marine channels permanently prevented the ice from inundating the landscape it once crossed. England argued that tectonics, not climate, have led to a fundamental change in glacial style and therefore, it is incorrect to use the maximum distribution of erratics in the context of the present topography in order to carve out these fiords.

1.5.4 Summary

Clearly, the 'Innuitian Ice Sheet' and 'Franklin Ice Complex' models would seem to be mutually exclusive for the last glaciation. However, England (1981) suggested that the fresh glacial sculpture and striae indicating southward flow on east-central Ellesmere Island could possibly be the result of local ice that may have built up due to the glacio-climatic influence of major polynya, such as the 'North Water' in Baffin Bay today. This polynya has presently produced a substantial increase in snow accumulation on southeastern Devon Island and Thule Peninsula, Greenland (Koerner, 1966 and Mock, 1968, respectively). England proposed that this same phenomenon occurred in previous glacial regimes.

The equivocal nature of the problem is also illustrated in a study of ice-marginal landforms on west-central Ellesmere Island by Hodgson (1985). He found no reliable evidence for a complete ice cover of western Ellesmere Island and Eureka Sound in the last glaciation. He concluded that neither a pan-archipelago ice sheet nor a simple expansion of present ice caps could adequately explain his observations, however, deglaciation and emergence of west-central Ellesmere Island was found to follow the general pattern of the Franklin Ice Complex model.

1.6 Characteristics of High Latitude Tills

In the Canadian High Arctic, the till is generally thin and discontinuous, probably due to the cold-based nature of the glaciers (Scott, 1976). Thicker till is found in some lowland areas adjacent to inter-island channels, derived from unconsolidated marine sediments. Similar observations have been made by Boulton (1970) in Svalbard, where glacial till is relatively rare. At most of the localities studied, the glacier sole lay directly on smoothed and striated bedrock. The largest pocket of till measured only 5 m in length and 30 cm in depth. High latitude tills are generally much thinner as compared to tills further south, e.g.

Canadian Shield tills are typically 2 to 8 m thick and over 30 m thick in some buried valleys (Scott, 1976).

Debris in glaciers can be derived from the atmosphere, from rock walls overlooking a glacier or at the glacier bed. Due to the lateral extent of the ice sheet, most high latitude till characteristics are best explained by entrainment at the base of the glacier (Gemmell *et al.*, 1986). In the Canadian High Arctic, till derived from underlying bedrock may be weatherd (Scott, 1976) or fresh or only superficially weathered (Gemmell *et al.*, 1986). In terms of the granulometry, Innuitian Province till is typically a mixture of stones, fine sand, silt, and clay but it may vary from rubble, over resistant sandstones and carbonates, to silty clay over poorly consolidated shales (Scott, 1976). Greenland tills are composed of mainly sand and fine gravel with considerable variation in the size distribution of individual samples, even from a single band (Sugden *et al.*, 1987). In some tills there is a bimodal distribution, typical of glacial crushing, with one peak representing the grain size of the gneissic parent bedrock and the other rock fragments (Sugden *et al.*, 1987). In most cases the debris bands are free of clay-size particles typical of glacial abrasion. Probably, this reflects the periodic flushing of the ice-rock system by meltwater (Gemmell et al., 1986; Boulton 1970; Sugden *et al.*, 1987).

In conclusion, there are three main characteristics of high latitude tills: 1) they are thin and discontinuous, 2) they contain a low amount of clay-size particles and 3) their lithology mirrors the local bedrock.

2. PROVENANCE STUDIES

This chapter briefly outlines the principles involved in provenance studies, the underlying assumptions and weaknesses, and attempts to place the present study in the context of the limitations of this technique.

2.1 Glacial Deposition

A complex combination of interrelations operates between an ice sheet and the bedrock lying beneath it, leading to the erosion, transport and deposition of material. Since the transport of material serves as a direct measure of the work done by a glacier, observations that yield information on transport of glacial debris are important in deducing the directions of former glacial flow.

'Glacial drift' is a general term that encompasses all the materials transported and deposited as a result of glaciation. However, most provenance studies are carried out on 'till'. This is a heterogeneous sediment deposited directly from the ice without the direct aid of meltwater. Till is dominantly unsorted with respect to grain size and may consist principally of clay particles, or of large boulders, or any combination of these and intermediate sizes. Types of till and their modes of deposition can be found in Flint (1971), and are summarized below:

Lodgment till is deposited at the base of a glacier. The particles in this type of till are 'lodged' in the accumulating drift, under pressure, on the subglacial floor during both its advance and retreat (if the terminal zone is actively flowing during shrinkage; Fig. 2.1a). Ablation till is deposited from drift in transport upon or within the terminal areas of a thinning and melting glacier (Fig. 2.1b). Ablation is defined as the process by which substances, including ice, are lost from a glacier during evaporation and melting. Ablation till is usually deposited on top of a lodgment till as the ice melts away and the drift is moved

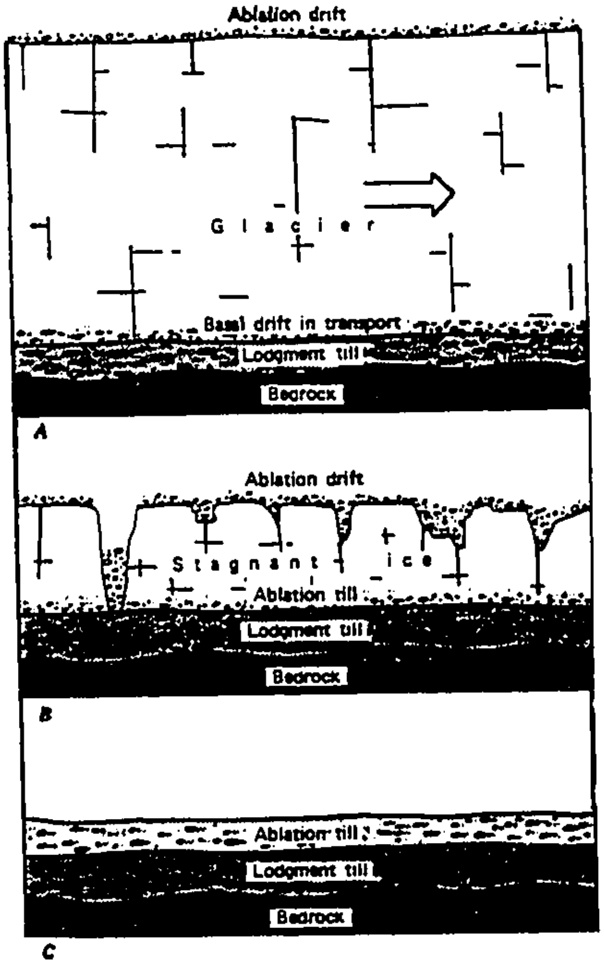

Figure 2.1 Origin of lodgment till and ablation till. a) Material eroded by the base of the glacier is lodged over the bedrock to form lodgment till. b) As the nearly stagnant glacier melts, ablation till is deposited from the basal zone of the ice. Water has removed most of the fines. c) Postglacial condition with lodgment till underlying ablation till (Flint, 1971).

towards the ground by any one of several processes (e.g., dumping, sliding, subsidence; Fig. 2.1c). For the purposes of provenance studies, it is preferable to sample basal (lodgment) till because it reflects the complex flow patterns of the late stages of glaciation, when ice is thin and easily diverted by topographic obstructions.

Provenance studies make use of the fact that glaciers erode and transport material from the bedrock over which they flow. The eroded material is redeposited in patterns called dispersal 'trains' or 'fans' which consist of a series of erratics that have come from the same source. The trains may appear either as lines of erratics, such as are often found in the down-valley direction of a valley glacier, or as fans of erratics, with the apices at places of origin which can often be traced for many kilometers (Fig. 2.2a). The 'fan' shape can result from divergent flow inherent in the spreading of glacier ice, or from change in flow direction, caused either by the increased influence exerted by topography as the ice sheet thins or by shift in the accumulation of snowfall during the growth and decay of an ice sheet. The width of the fan's arc is determined by the arc through which the shift in direction occurred after erosion of the rock at the source of the fan began. Probably most linear forms were made at so late a date that no shift in direction of flow occurred subsequently.

Mapping dispersal trains can indicate the provenance of the transported rock debris,0 as well as give an indication of the direction of ice flow (Fig. 2.2b). Although the line drawn from the location of an erratic back to its place of its origin parallels in a general way the streamline forms and other evidence of glacier movement between the two points, such a line is not, of course, its true path of travel. In addition to their usefulness as indicators of lateral movement of glacier ice, erratics can also demonstrate a vertical component of motion in an ice sheet (Wright, 1937, p. 67-68).

A till sample can be broken down into four major particle-size classes (Shilts, 1971) : i) coarse fraction (large boulders to 0.25 mm), ii) fine sand fraction (<0.25 mm and >0.062 mm), iii) silt fraction (<0.062 mm and >0.002 mm), and iv) clay fraction

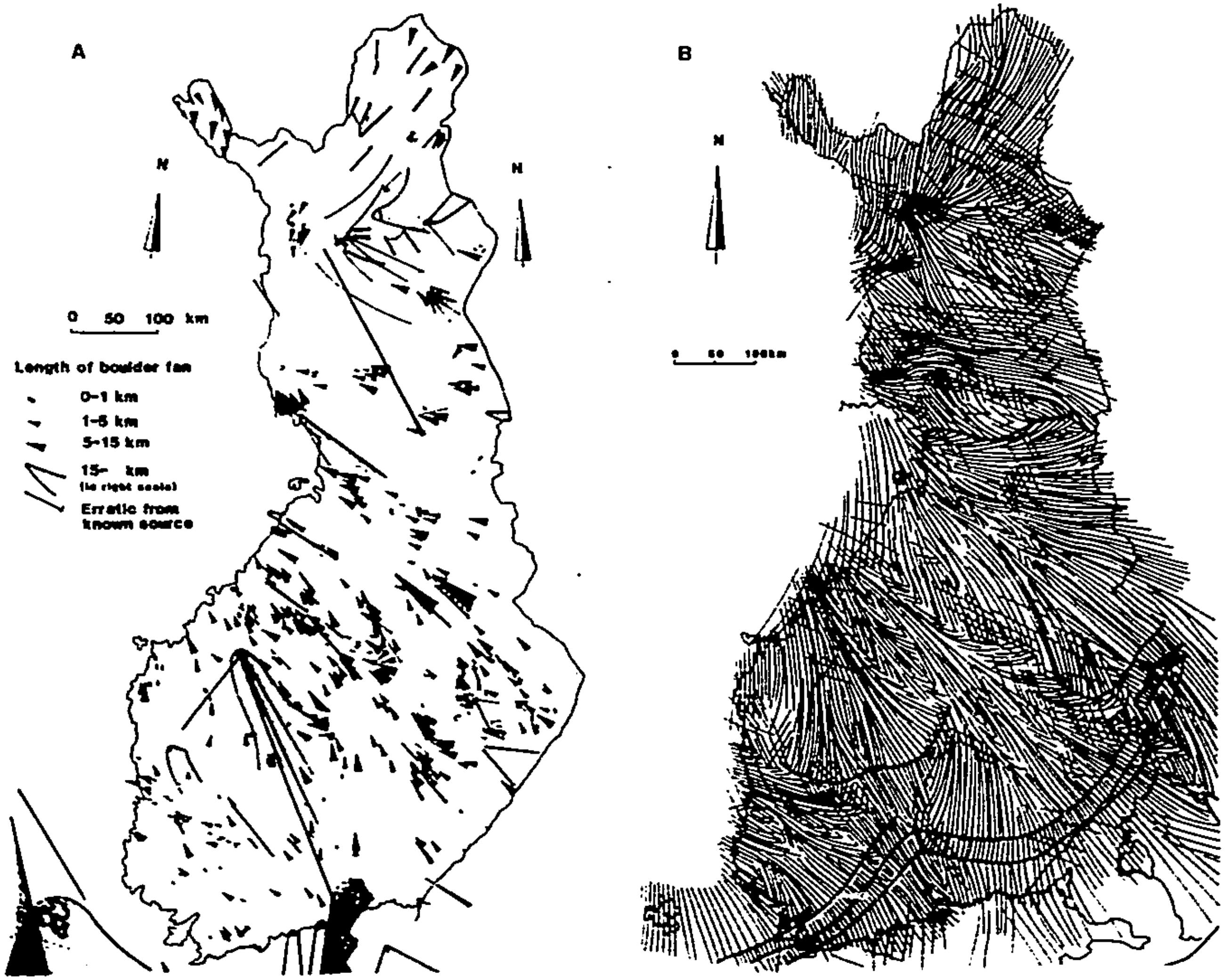

Figure 2.2 Ice flow indicators in Finland (Salonen, 1985). a) Dispersal fans of glacial erratics. b) Flow lines (light lines) of the Scandinavian Ice Sheet, and major marginal and interlobate formations (heavy lines).

(< 0.002 mm - colloidal size). The larger of the coarse size fractions is usually identified by visual inspection. Boulder and stone 'counts' are often made in the field, as a way of determining the concentration of a particular rock type in the till. Occasionally, thin sections are made so that a particular clast can be identified by high resolution. The smaller granule size fraction (2 to 4 mm) can be resin-mounted, made into thin sections and examined under the polarizing microscope (Bouchard and Salonen, 1988). Sand-sized fractions are examined using the stereomicroscope and heavy and magnetic minerals may be separated. Geochemical and X-ray diffraction analysis can be performed on the silt and clay size portions. The granulometry and Munsell colour can be investigated for the sand, silt and clay size portions.

Many provenance studies use distinctive rock lithologies of erratics or the proportions of various minerals or lithologies (in the case where no single distinctive indicator is present). Although most provenance studies include the investigation of two or more grain sizes of the till, other indicators might include microfossils, fossil pollen grains, and the degree of rounding and frosting in quartz grains. Once the lithology of the drift has been investigated, it can then be combined with morphologic and stratigraphic relationships to determine the former configuration and flow direction of glacial lobes. Morphologic directional indicators include the products of glacial erosion, for example, hanging tributary valleys, fiords, large ice flow forms (such as roche moutonnées) and on a smaller scale, striations, small grooves and crescentic marks. The till fabric, that is, the arrangement of its component rock particles, is also useful in determining the direction of movement of a glacier at the time of till deposition, possibly with greater accuracy than using streamline forms, striations, etc. (Flint, 1971).

2.2 Lithologic Relations of Till to Bedrock

For provenance studies to be successful, the erratic trains must have lithologic characteristics distinctive from the local bedrock, and the probable source area should be restricted in outcrop. Flint (1971) identifed three factors that control the proportion of a given kind of rock in the till:

i) The area of outcrop of the source rock upstream.

ii) The erodibility, determined by rock hardness. For example, igneous and metamorphic rocks yield less readily to mechanical erosion than do shales and limestones. In addition, all conspicuously jointed hard rocks yield till composed of boulders and large stones contained within a relatively small amount of sandy matrix. Limestones and dolomites yield boulders and smaller stones in an abundant matrix of clay and silt consisting in large part of tiny fragments of limestone. Shales yield till that is largely clay.

iii) The durability in transport. The greatest dissimilarities between the proportions of rock types in till and the kinds of bedrock from which they were derived result from transport of nondurable rocks such as sandstones and schists, which evidently break up or wear out in transit to a greater extent than more durable rock types. A process of natural selection takes place in transit, resulting in survival of the toughest, which usually travel the farthest (as much as 800 km from their sources).

According to Flint (1971), coarse fractions (pebble, cobble and boulder), are most likely to have travelled the shortest distances (tens of kilometers). However, the reverse can also hold true -- coarse grain-size erratics are much further travelled than the matrix, derived from more erodible sedimentary rocks. The fine-grained fraction (sand, silt, and clay sizes) is more difficult to evaluate as to source, but it is likely that much is of more distant origin, and has been ground up to its small size by mechanical wear en route. Thus, it has become diluted by other kinds of rocks. As a consequence, till, particularly the coarse fraction, tends to reflect the lithology of the bedrock from which it is mainly derived and a single till sheet can vary greatly in composition from one area to another.

2.3 Limitations and Weaknesses

The results of provenance studies are limited by three factors: i) the sampling density, ii) the sample depth and iii) the grain size considered.

i) Ideally, sampling for provenance and associated geochemical analysis is carried out in a grid pattern on one of three scales: detailed (hundreds of metres), local (tens of kilometres) or regional (hundreds of kilometres), or a combination of these scales. Sampling on too large a scale results in anomalies that are generally weak (highly diluted) and difficult to interpret.

ii) Typically, till is sampled at various heights above the bedrock, in order to determine if more than one type of till is involved. If the area lacks suitably deep exposures, sampling is made at depth, generally between 60 to 100 cm below the surface. In areas underlain by deep, continuous permafrost, sample pits are typically 50 to 100 cm deep with unfrozen material collected from the walls of the pit.

Sampling at depth is critical since postglacial weathering can have a profound effect on the geochemistry of glacial sediments to considerable depth, depending on the depth of the permafrost and water tables (Rencz and Shilts, 1980) and the permeability of the sediment (Shilts, 1984). In areas of permafrost, mechanisms such as cryoturbation (frost heave) and the transport of fine particles and ions by water, driven by cryosuction, are perhaps more significant than in warm regions. Soil process studies have been carried out on southern Victoria Island, N.W.T., to evaluate the severity of the masking effect caused by the variation of till characteristics within the weathered soil zone (Nixon and Sharpe, 1986). An upper weathered sample (collected at a depth of 40 cm) was compared with a sample from the base of the pit (collected as much as 90 cm below the frost table). Consistent textural and geochemical trends in the soil profiles could be recognized, but the patterns were explained only partly in terms of accepted pedological processes active in a temperate environment.

iii) The grain size considered may or may not have an influence on the results of provenance studies, as illustrated by the following studies:

Dreimanis and Vagners (1983) studied the lithologic relation of till to bedrock (dolomite) in southwestern Ontario. During glacial transport, particularly as basal drift, each rock eventually became comminuted to the terminal grade of its consituent minerals. This terminal grade was typical for each mineral. Before the carbonate rocks were comminuted to the terminal grades of their constituent minerals, their grain size distribution curve was bimodal or multimodal, with rock fragments being of one or more coarse-grained modes and each constituent mineral possessing its own fine-grained mode. The coarse-grained mode was larger than the fine-grained mode if the bedrock source was local, and the fine-grained mode became predominant when the bedrock source was distant. By contrast, a study of 16 size fractions in 11 till samples in Indiana, U.S.A., near the boundary of the last glaciation, showed no significant differences in lithologic composition (Harrison, 1959; 1960). Harrison concluded that the abundance of various lithologic components of the till was proportional to the size of the corresponding bedrock area traversed by the glacial lobe. For provenance studies, in general, the optimum size fraction varies from area to area, depending on the durability of the coarse fractions and the weathering, size and stability of fines.

The weakness of provenance studies arises from the lack of understanding of modes of till deposition and the presence, in some cases, of multiple till layers representing multiple ice advances, not all of which necessarily travelled in the same direction. For example, there is often confusion in distinguishing ablation till facies from lodgment till facies. The problem of distinguishing different till sheets can often be resolved on the basis of lithology, geochemistry, fabric and mechanical distribution.

2.4 Applications

2.4.1 Glacial History

Provenance investigations have long been used to decipher both local glacial history and long distance transport in areas of continental glaciation. Over fifty years ago, the Red Jasper conglomerate was used as a tracer bed to determine the limits of the distribution of the Wisconsinan and Illinoian drift (Slawson, 1933). The source of the bright red Jasper and translucent quartz pebbles in a matrix of pure white quartzite is a small area of outcrops lying approximately 64 km east-southeast of Sault Ste Marie. This easily identifiable rock with restricted outcrop is a perfect example of an excellent tracer bed.

More recently, Shilts (1980) used pebble-sized erratics to determine the pattern of glacial dispersal around Hudson Bay. He was able to show that the central portion of the North American Laurentide ice sheet was made up of at least two land-based centers. Klassen and Bolduc (1984) investigated the distribution of erratics in conjunction with a study of striae and sculpture in the vicinity of Churchill Falls, Labrador. Dispersal trains at regional, local and detailed scales were identified, enabling the identification of two principal phases of regional ice flow and an estimate of the location of the Labradorean dispersal center of the Laurentide Ice Sheet prior to late Wisconsinan time.

The stone count technique was used to differentiate between the former presence of regional Laurentide ice and limits of local glacier expansion in Nachvak Fiord, northern Labrador (Bell *et al.*, 1989). Five lithologic groups were identified and their percentages plotted on a map which provided a basis for describing the extent and flow direction of ice sources. The stone counts were then grouped according to their lithological composition using cluster analysis, which uses a hierarchial clustering procedure based upon a measure of similarity between the composition of individual samples. The similarity was measured using the Euclidean distance between two samples given by the root mean square of the differences in values for each lithological class. A dendrogram of the cluster solution is shown in Figure 2.3a. A map was then made to illustrate the general pattern of cluster distribution (Fig. 2.3b) from which flow directions were inferred. Using this technique, one population related to local glacial transportation and a second population consisting of material belonging to more distant bedrock sources were identified. Statistically treated pebble lithology data, geomorphic relationships and radiocarbon dates on associated marine and glaciomarine sediments enabled Bell *et al.* (1989) to propose two possible models for Middle and Late Wisconsinan glaciation in northern Labrador.

Statistical analysis of boulder counts in morainic materials in southern Finland identified two naturally distributed populations, which were found to be connected with the glacial dynamics and basal temperature regimes of the last Fennoscandian ice sheet (Salonen, 1984). One population, consisting primarily of local material, was determined to have been deposited near a receding glacial front. A second population, consisting of more distantly transported boulder material, originated from an earlier melting-freezing transition zone. The results were based on equifrequence curves and cluster analysis using the χ^2 test.

In the North Cascades, Washington, Heller (1964) used stone count data, equilibrium-line altitude reconstruction and stratigraphic relations to interpret Late Wisconsinan ice flow directions. Stone count diagrams, which are modified rose diagrams of rock types (grouped by provenance) plotted radially away from the center, were used to correlate deposits and determine flow directions. Similarily, the identification of multiple drifts, the direction of ice movement and the location of concealed bedrock were investigated using isopleth maps of pebbles in tills of Montana and North Dakota (Howard, 1956).

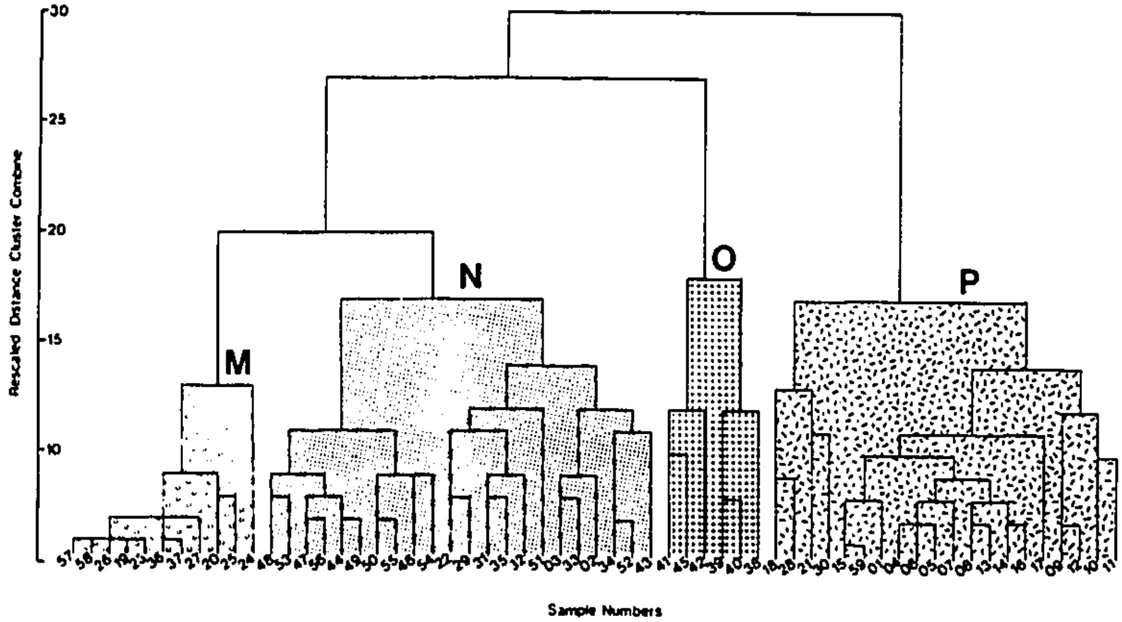

Figure 2.3a Application of cluster analysis to interpretation of ice flow directions in Labrador (Bell *et al.*, 1989). Dendrogram based on lithological composition of pebbles in tills.

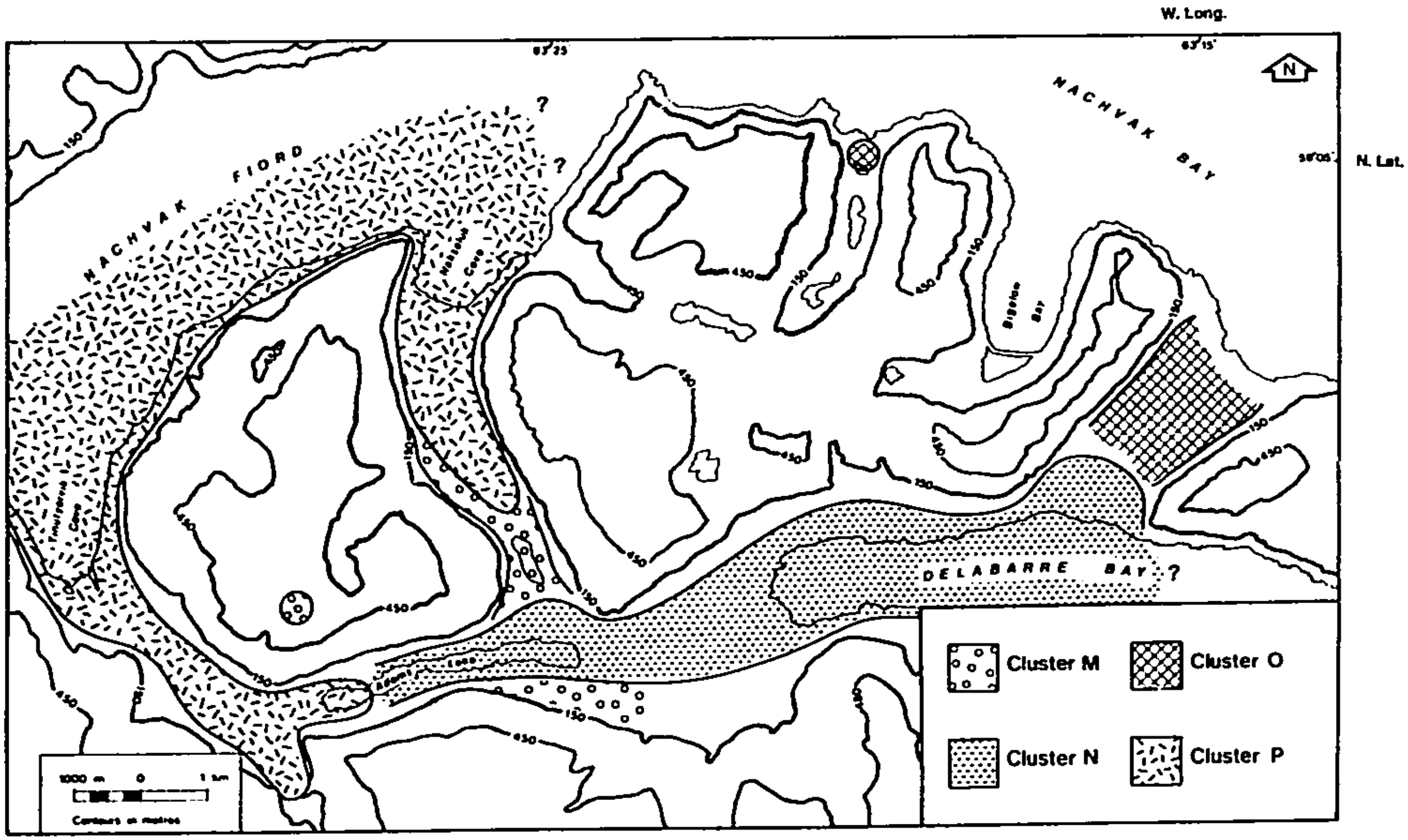

Figure 2.3b Geographic distribution of the sample clusters in Fig. 2a (Bell *et al.*, 1989).

In the Finger Lakes and Catskills, New York, Moss and Ritter (1962) identified two drifts, located in adjacent areas, using pebble lithology. Sand/silt/clay ratios and the percentage of iron-oxide coated, uncoated opaque and uncoated non-opaque heavy mineral grains also proved to differ greatly in the tills in these two areas (Fig. 2.4a,b). This information combined with glacial features and pebble fabrics established two predominant directions of ice movement (Fig. 2.4c).

Dreimanis (1961) made a study of the tills of southern Ontario, which differ lithologically and texturally not only from one area to another, but even in single sections. He made use of a variety of properties -- granulometric composition, carbonate content, lithologic composition of the sand, pebble and boulder grades of till, and heavy mineral analysis -- as an aid in determination of local glacial movements.

Provenance studies carried out in the course of prospecting have often resulted in an improved knowledge of local glacial history. For example, boulder- and pebble-size clasts in conjunction with heavy mineral analysis were used to determine source areas and ice flow paths in the Pioneer Mountains, a deglaciated mountainous region in Idaho (Evenson *et al.*, 1979). Statistical analysis of heavy minerals (varimax rotated R-mode factor analysis and Q-mode cluster analysis) established 5 unusual flow patterns: i) up-canyon glacier flow, ii) divide crossing, iii) readvance of individual ice lobes creating cross-cutting relationships, iv) ice rafting into ice-dammed marginal lakes, and v) jökulhlaup activity. The authors concluded that sampling across an active- or former-glacier terminus provides representative material from the entire catchment area which then permits the tracing of any resulting indicator of mineralization to the approximate source area. Conversely, as local glacial processes in an area become better understood, the importance of glacial history, former ice-flow and sediment transport directions can be applied to mineral exploration.

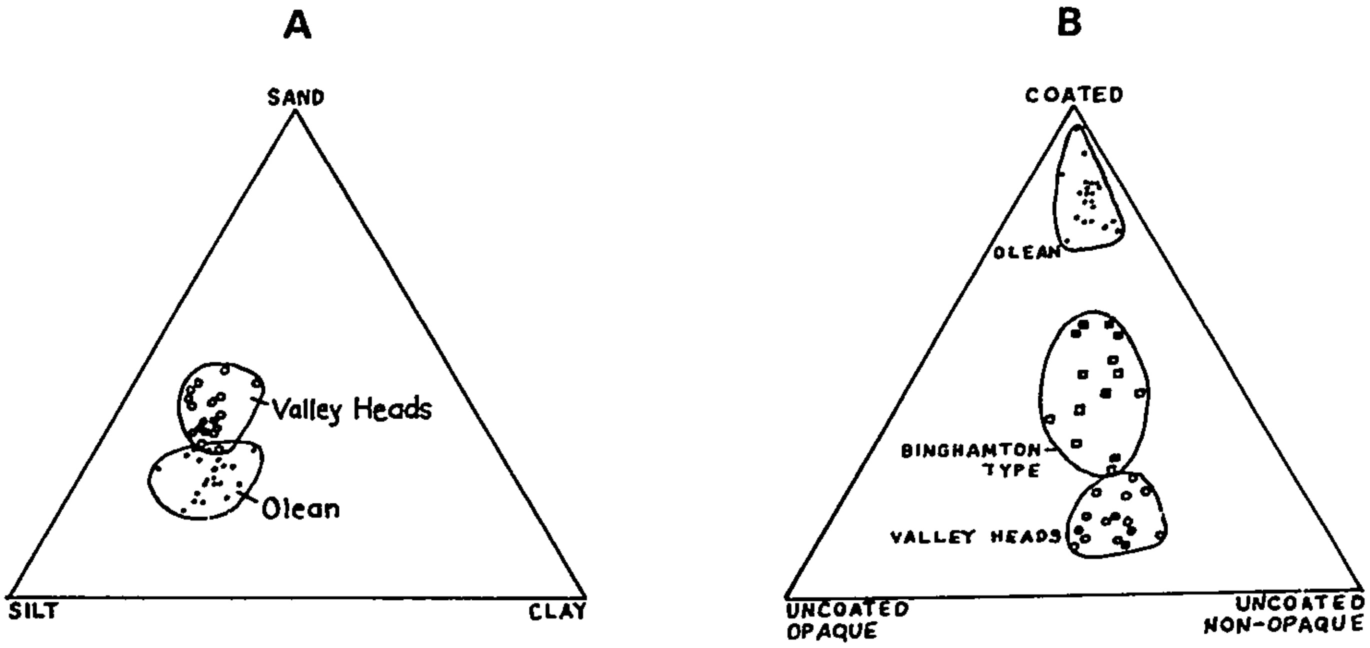

Figure 2.4 Ternary diagrams representing properties of tills in New York State (Moss and Ritter, 1962). a) Sand/silt/clay ratios of Olean and Valley-Heads tills. b) Proportions of iron-oxide coated, uncoated opaque and uncoated non-opaque heavy mineral grains of Olean and Valley-Heads tills, in Binghamton, New York.

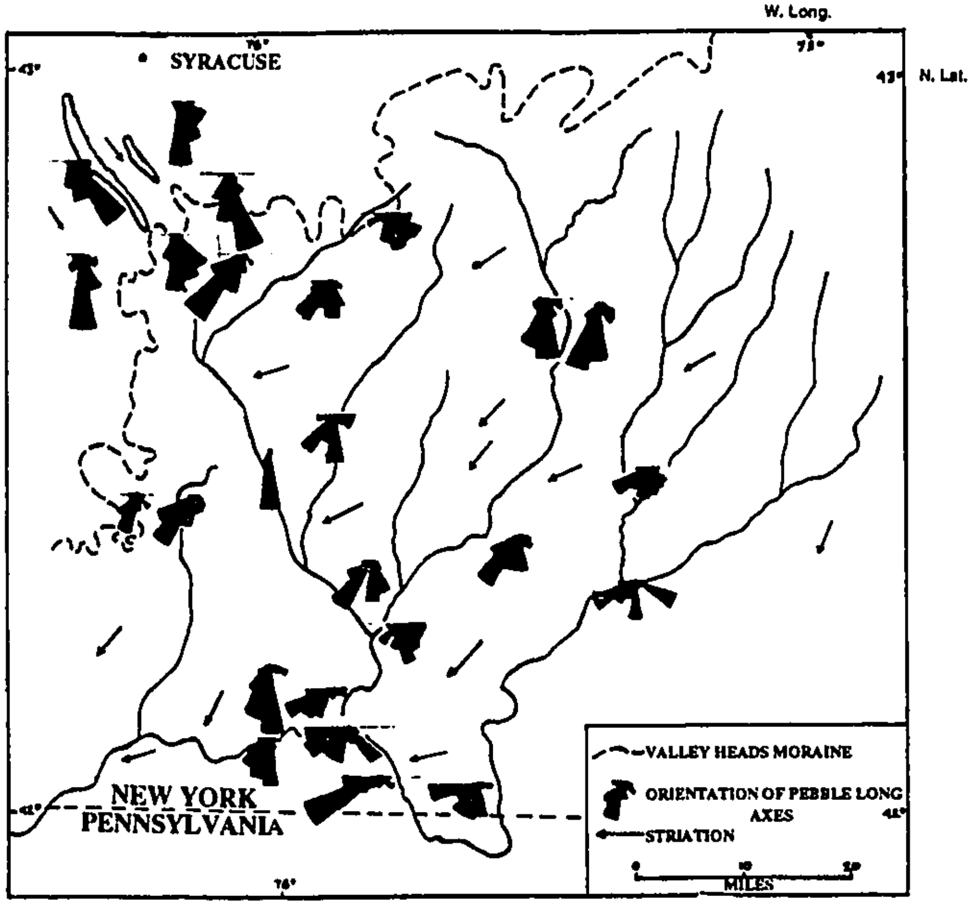

Figure 2.4c Map showing the orientations of striae and of long axes of pebbles (in the form of rose diagrams) in tills in New York State. This information supported the results of lithological, heavy mineral and textural analyses from which the authors interpreted two flow directions: Olean ice advanced in a southwesterly direction and Valley Heads ice moved into the area from the northwest, cutting diagonally across the direction of the earlier Olean advance (Moss and Ritter, 1962).

2.4.2 Prospecting

Prospecting in formerly glaciated terrains makes use of the fact that the concentrations of glacially deposited material (elements, minerals or rocks) reach a peak at or close to their source, and decline exponentially in the direction of transport (Shilts, 1976). The concentration decreases rapidly in the area immediately down-ice from the source in the area of the dispersal 'head', and more gradually at greater distances near the dispersal 'tail'.

Before reconnaissance mapping is carried out to detect the dispersal tail, a study is made of the local glacial stratigraphy and ice movements. In this way, the sampling can be conducted in a rectangular grid, the lines of the grid being perpendicular to the recognized flow directions in the region. The lines and sampling spacings of this grid are dependent on the expected size of the ore body. Basal till is commonly sampled by drilling, but can also be collected from shallow pits, natural and man-made exposures. Reconnaissance sampling to identify anomalies is followed by detailed sampling to delineate the head of the dispersal fan (Fig. 2.5). This technique delimits indicator trains which are typically finger- or ribbon-shaped.

Over 450 boulder trains have been identified in Finland in the course of prospecting for sulfide mineralization. They are normally some 1 to 5 km in length, but show great variation, with the longest examples being 50 to 100 km (Salonen, 1985). These fans characteristically coincide in orientation with the last or most pronounced direction of glacial flow, occupying a sector of approximately 10°. This angle may be considerably wider if the fan is a product of a number of ice flows of varying direction. Thus, fans opening up to angles of as much as 90° have been described in eastern and northern Finland in particular.

Traditionally, drift sampling was largely limited to easily traceable 'float' or ore boulders. Mapping of 'float' trains led to the discovery of numerous iron-ore, gold, base metal, and nickel deposits in Canada (a review of these discoveries can be found in

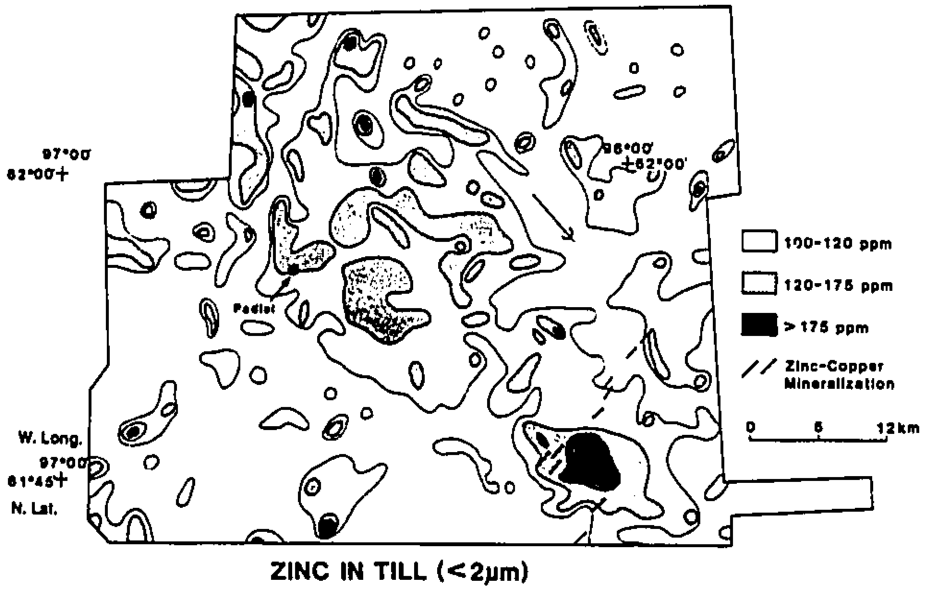

Figure 2.5 Zn concentration indicated by mapping on a local scale in the Keewatin, N.W.T. Map based on over 1000 samples collected on a 1.6 km x 1.6 km grid (Shilts, 1984).

Dreimanis [1958] and Dilabio [1981]). With the improvement of analytical tools (e. g. atomic absorption), the finest fractions of till -- silt and clay -- can now be easily analyzed to determine their mineralogic and chemical composition. Today, prospectors make use of several grain size fractions including heavy clasts (rock fragments with pieces of attached ore, fragments of ore minerals and certain pathfinder minerals that are diagnostic of favorable host rocks) and heavy minerals, which are analyzed chemically for base metals. Ores of many metals have a high specific gravity and many other heavy minerals are commonly associated with ore bodies (Levinson, 1974).

The geochemistry of till and its application to prospecting has been the subject of numerous investigations by Shilts (1971, 1973, 1977). He has made several conclusions about the optimum size fractions for geochemical analysis. The combination of two or more fine fractions (such as silt and clay) is not recommended for geochemical analysis because of compositional variances between size fractions, e.g. quartz is comminuted to a terminal grade of sand, clay minerals to a clay size fraction, etc. (Shilts, 1971). There is a preferential enrichment of trace minerals in the <2 μm grain size in phyllosilicate minerals because of their high total surface area and exchange capacity (Coker, 1991).

In perennially frozen areas, the clay-sized fraction is recommended for analysis rather than heavy mineral separates from near-surface till samples because of the possible destruction of sulfide minerals and mineralized rock fragments by post-glacial mechanical and chemical weathering, which takes place within the active layer overlying the permafrost (Shilts, 1972). The problem of obtaining unweathered material in areas underlain by shallow permafrost has been solved by sampling mudboils, which are the product of till reworked by cryoturbation (Dyke, 1980; Shilts, 1977). Thus, the sediment collected 10 to 80 cm beneath the surface of the mudboil is not weathered to any greater degree than the material just above the permafrost table.

Boulder- and pebble-sized fractions are commonly investigated in conjunction with till fines and they can even be more useful than the fines, in some cases. For example, chalcopyrite-bearing pebbles in the area of Lac Mistassini, Québec, were found to be a more efficient guide to the source of the copper ore than the analysis for copper in the soil developed on the dispersal train (DiLabio, 1981). Chalcopyrite had a clast mode between 8 and 1 mm and a matrix mode from 0.063 to 0.016 mm. The clast mode developed after short transport distances and the matrix mode required at least 100 km of transport to develop.

Similar conclusions were reached by Szabo *et al.*(1975), in a study of the dispersal trends of elements and indicator pebbles in till at Mount Pleasant, New Brunswick. Size fraction analysis showed that the coarse fraction of the till had a more extensive and intensive anomaly than the fine fraction for each metal analysed. Cu, Pb, and Zn had dispersion trains of 2 to 5 km in the minus 80-mesh size fraction, whereas, the dispersion train in the coarse fraction exceeded 16 km from a mineralized source. Analysis of heavy minerals delineated trains of 10 to 15 km or more.

In a study in eastern Finland, a comparison of the geochemistry of the fine and coarse fractions (boulders and pebbles) of tills was carried out to determine whether or not each fraction reflects the composition of the underlying greenstone bedrock (Saarnisto and Taipale, 1985). Eight trace metals were analysed by atomic absorption spectroscopy. The proportion of the greenstone material in the fine fraction of the till was found to be smaller than in the coarse fraction (Fig. 2.6). By contrast, in the Lac-Mégantic region, Québec, trace elements, minerals and boulders were found to have comparable dispersal patterns (dispersal bands were detected up to 64 km away from sources of ultramafic rocks; Shilts, 1971).

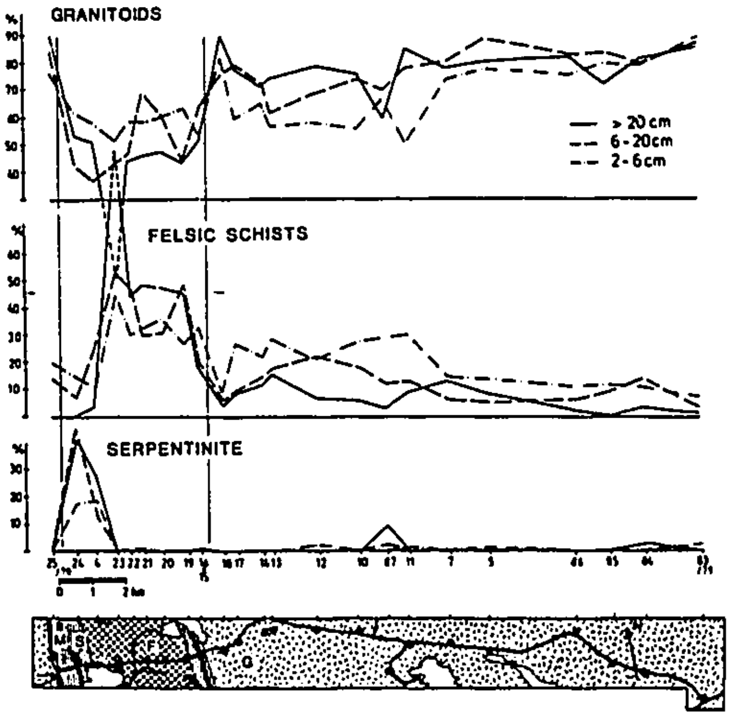

Figure 2.6 Distribution of granitoid, felsic schist and serpentinite erratics in till along a survey profile in eastern Finland. Surficial boulders (>20 cm), stones (6-20 cm) and pebbles (2-6 cm) were investigated separately. Legend for the bedrock map: G = granitoids, F = felsic schists, M = mafic and ultramafic volcanite, S = serpentinite. The till composition reflects the narrow serpentinite zone (Saarnisto and Taipale, 1985)

In all dispersal mapping, a study of past glacial processes is an integral part of successful prospecting. Any improvement to the understanding of glacial history, former ice flows and sedimentary transport may have a considerable bearing on the interpretation of geochemical dispersal patterns, even at a local scale (Shilts, 1984).

3. METHODS

As described in the introduction, the main purpose of this study was to identify the direction of former ice flows in east-central Ellesmere Island and then put the glacial history in a regional context. This was accomplished by making stone counts on the till surface to determine the lithology of the coarse fraction of the till. The fine fraction of the till (sand/silt/clay) was collected in order to study the granulometry, geochemistry and Munsell colours. This chapter presents the details of field and laboratory methodologies. The results and their statistical treatment are given in detail in Chapter 4.

3.1 Site description

In terms of bedrock geology, the study area in east-central Ellesmere Island fulfills the two main requirements for a provenance study: i) geological formations with distinctive lithologies give rise to erratics in the till and ii) these formations have relatively restricted source areas. However, the interpretation of the results at this site was hindered by the relatively low sample density and by the fact that the very thin till cover only permitted surface sampling. The unknown nature of the bedrock underneath the ice caps also limits the possible interpretations of former glacial flow.

3.1.1 Sampling Density

Ice caps cover most of the study area, extending to less than 1 km of the coast with numerous glaciers reaching sea level. The only large areas completely free of permanent ice are Bache Peninsula, Knud Peninsula and Pim Island. Most of the ice-free areas are covered by snow for nine months of the year, from September to May, and north-facing slopes often have snowbanks until June or July. Exceptions are places which are either blown free of snow or protected sites where there is a microclimate, such as the Arctic 'oasis' at Alexandra

Fiord. For practical reasons, sampling was restricted to the snow-free coastal areas above the marine limit, that were accessible by helicopter or snowmobile. Sampling was further limited by the fact that much of this terrain was barren of till. The result was a very unevenly-distributed grid of sample sites over the study area. The highest concentration of sample sites is in the Cape Herschel area, which was easily accessible from the base camp on foot. The lack of extensive drift deposits meant that sampling at regular intervals, the technique commonly employed for geochemical analysis, was simply not possible in the study area. Consequently, the sample density is low (0.012 sites per km^2), compared to the range of geochemical sampling commonly used in prospecting (0.2 to 2 samples per km^2).

3.1.2 Sampling Depth

In studies at lower latitudes, till samples for stone counts and geochemical analysis are normally collected at a minimum of 50 cm below the surface in order to avoid the effects of chemical weathering, cryoturbation and aeolian input. However, over much of this study area, the till is only 5 to 10 cm thick. Areas of thicker overburden are underlain by continuous permafrost that thaws to a maximum depth of only 40 to 50 cm. Thus, subsurface sampling was impossible at many sites due to the thin veneer of till and the shallow depth of permafrost.

Although the precise effects of chemical and physical weathering on till chemistry in this study area are not known, the consequences of weathering and frost action can be observed on the surface of the till and bedrock:

On the surface of the till, particularly in near-coastal and coastal areas, efflorescences of sodium salts can be observed, including thenardite (Watts, 1981). It has not been established whether these salts originated from sea spray, from earlier marine incursion or from the dissolution of Paleozoic evaporites. In upland areas, notably Cape Herschel and Alexandra Fiord, many of the mafic erratics are encrusted with a rind, composed primarily of calcium carbonate and sodium chloride (Swett, 1974; Watts, 1981). Salt rinds also may be derived from the leaching of hornblende within the rocks (Bradley *et al.*, 1978). Incipient weathering features such as grus accumulations, spalled crusts, exfoliated joint blocks, differentially eroded dykes and weathering pits are common to the Precambrian bedrock. Flaking of tor (i.e. bedrock) surfaces is a presently occurring phenomenon in the High Arctic, indicated by accumulations of grains on recent snowbanks resting at the base of the exposure. Micropits (up to 5 cm across and 2 cm deep) which cover outcrops in patches up to 10 m across are attributed to solution weathering related to snowbank melting in the summer (Watts, 1981). Microfracturing of the pits is caused by hydration and crystallization of salts. In addition, conditions of high wind and fog are known to favour surface microfracturing during the summer months (Watts, 1983). The open water in Nares Strait (or "North Water", Müller *et al.*, 1975) is the source of moisture, especially in the summer months.

Frost action is indicated by frost boils and solifluction lobes (notably on low coastal areas at Cape Herschel). In addition, *in situ* frost-heaved blocks are found where standing water occurs, as in upland basins excavated in bedrock or where snowbanks inhibit runoff (Potts, 1970).

The composition of surface sediments may also be changed by the addition of wind-transported material, particularly in a very windy environment such as the High Arctic. In the study area, small amounts of wind-transported debris are found in the snow. Upon snow-melt, this sediment becomes incorporated into the till.

3.2 Field and Laboratory Methods

Ninety-six sites were sampled in the study area during a total of 67 days of field work conducted between May and August in the summers of 1985, 1986 and 1989. Three samples were taken at each location where possible: i) All of the stones between 1 and 4 cm in diameter were collected from a 60 x 60 cm quadrat on the surface of the till (Plate 3.1). (The overburden was identified as till at all sites by W. Blake, Jr.) Level sites, free of vegetation, were randomly chosen in an *a priori* homogeneous area. All stone counts included more than 100 pebbles. No stone counts were made adjacent to the quadrats because of the scarcity of suitable sample sites. With 3 exceptions, all sites were above the inferred limit of Holocene marine submergence of 80 to 100 m (W. Blake, Jr., personal communication). Therefore, the possibility of ice-rafted debris being deposited as beach material has largely been eliminated. ii) Bedrock samples were taken in order to distinguish between locally-derived stones and glacially-transported material. All stone counts sites were in areas of Archean crystalline bedrock, with the exception of site 93, which was located on Paleozoic Arctic Platform bedrock. iii) A bulk sample of approximately 1 kg of till was collected from the surface or slightly below, wherever possible.

3.2.1 Stone Identification

Neohelikian and Paleozoic erratics in the stone counts were identified using: i) bedrock collections from Bache Peninsula made by Christie in 1982, ii) field descriptions recorded by Christie, and iii) Christie's description of the 'Inland Suite' and 'Cape Suite' rocks (Christie, 1983). Although over 20 formations have been mapped in the study area (Christie, 1967; Frisch 1988), only 3 groups of rocks were identifiable as erratics in the till, because of their distinctive lithologic characteristics and limited areal outcrops. The 3 groups are: i) the Archean crystalline granites and granitic gneisses, ii) the red and green Neohelikian Thule Group rocks and iii) the light-coloured Paleozoic clastics and carbonates.

i) Archean crystalline rocks are common erratics in the till, but they are of little diagnostic value since almost all of these rocks are so scattered and widespread in outcrop that it is impossible to trace erratics derived from them to a single source area. In addition, not all of the Archean basement has been carefully identified (some outcrops have been

Plate 3.1 A stone count quadrat on Cape Herschel plateau showing an abundance of light-coloured erratics.

mapped only as undifferentiated crystalline basement; Frisch, 1988). The only exception is marble, of which small outcrops occur in a dozen places on the tip of Knud Peninsula, Cape Isabella and on the north and south of Thorvald Peninsula (Fig. 1.3). Although the small number of marble erratics did not warrant distinguishing a special group for the purpose of data manipulation, their importance will be discussed separately.

ii) The lithologically distinctive beds and limited areal extent of the Thule Group make this formation the most useful for tracing erratic dispersal trains in the study area. Rocks found in the stone counts that are unique to the Thule Group are: a) red and green stromatolites, often with mottled colours, b) light green, red, dark purple and maroon shale commonly variegated and mottled, c) brick red shaly sandstone and d) a slightly arkosic, dark purple-brown sandstone which is poorly sorted and medium- to coarse-grained.

Although basalt erratics were found in a number of the stone counts, dykes and sills are not unique to the Thule Group but are scattered throughout the study area (Christie, 1967; Frisch, 1988). For example, basalt erratics present in two collections at the head of Baird Inlet (sites 6 and 7) most probably originated from dykes to the west (not shown on Fig. 1.3). Several of these dykes outcrop north of Ekblaw Glacier and they probably extend under the glacier, where they are eroded and transported eastward into Baird Inlet.

iii) Cambrian to Ordovician rocks, with the Bache Peninsula Member of the Dallas Bugt Formation at the base, are also widely distributed in the northern part of the study area, which limits their use as glacial tracers. A wide variety of these rocks was present in the stone counts including limestone, sandstone, arkose, intraformational breccia and conglomerate. Several small pieces of chert (black, turquoise and white) were found in the counts; chert is present as clasts in some of the conglomerates and as lenses in some of the dolomites in these units. Erratics of this unit are a variety of colours -- buff, light brown, grey, yellow, light green, brown and white. Dark grey-brown or buff algal limestones, common as erratics, also originate from these beds.

The restricted areal outcrop of the Eureka Sound Formation would make erratics from this unit ideal as glacial tracers. Unfortunately none were found during the fieldwork. The poorly consolidated sandstone and shaly coal which characterize this unit are unlikely to be preserved as larger erratics even if moved only a short distance. However, Christie (1983) did find fragments of brown sandy shale with black carbonaceous markings in a col atop Cape Herschel, which he believed to have originated from the Eureka Sound beds to the north. Christie found the debris at the approximate local limit of marine submergence, so the possibility exists that it was floated into place by sea ice (Christie, 1983).

iv) A fourth lithological group was added, since stones lithologically identical to the bedrock in the surrounding area were a significant component of most stone counts (Archean stones with lithologies different from the local Archean bedrock were counted as Archean stones). A problem arises in distinguishing between these locally-derived Archean material (which could be the result of frost shattering) and glacially transported Archean stones, since Archean rocks outcrop so extensively in the study area. Because of the great possibility that stones identified as being identical to the nearby bedrock could actually have been transported several kilometers or more, it is likely that the proportion of material attributed to frost shattering is unrealistically high.

For the purpose of statistical treatment of the data, the groups were given the shortened names -- Arch (for Archean), Thule (for Thule Group), Paleo (for Paleozoic rocks of Cambrian and Ordovician age),and Local.

3.2.2 Textural Analysis

Granulometry was performed on 95 till samples by the Sedimentology Laboratory at the Geological Survey of Canada, Ottawa. The textural classes used were sand (2000 to 63 μm), silt (63 to 2 μm) and clay (<2 μm). Grain size analyses of the 2 to 63 μm fraction were performed with sieves and for sediment <63 μm with the pipette.

3.2.3 Geochemical Analysis

The clay-sized fraction of 95 till samples was separated by centrifuging and decanting and analysed for Cu, Cr, Co, Mo, Mn, and Fe using atomic absorption after leaching with hot aqua regia by Bondar - Clegg Laboratories & Co., Ltd., Ottawa. W. Blake, Jr. arbitrarily decided which elements were analysed.

3.2.4 Munsell Colours

Munsell colours (Munsell Color Co., 1971) were compared with dry samples of the fine grain fraction (sand/silt/clay) for 76 till samples. The Munsell colour was identified in the laboratory under natural light. The Munsell colour is composed of three factors: the hue, 'value' and chroma.

4. RESULTS AND DISCUSSION

4.1 Stone Counts

4.1.1 General description

Appendix A gives the number of stones assigned to the 4 components -- Thule, Paleo, Arch and Local -- for each site. An average composition of the till can be estimated by the sum of all the stones of each rock type at all sites (given as a percentage of the total number of stones at all sites). This average composition is shown in a pie diagram, Figure 4.1, with the greatest proportion (78.2%) being Arch and Local components (which can be grouped with Arch since all but 1 of the counts were made in areas of Archean bedrock), followed by Paleozoic (18.7%) and a very small component of Thule (3.1%). The relative amounts of the rock types are similar to their extent of outcrop in the study area (Fig. 1.3).

Although the pie diagram shows the overall composition of the till in the study area, the distribution of the rock types among the sites can be represented in the form of frequency histograms. The 4 bar graphs in Figure 4.2 correspond to the 4 components of the tills. Each graph shows the number of sites where given stone concentrations were measured as a function of stone concentration. The stone concentration (abscissa) was calculated as:

$$\% \, x = \frac{\text{no. of type x stones at site}}{\text{total no. of stones at site}} \times 100$$

where x corresponds to the rock type. The y axis is the number of sites or samples. The stone concentrations were divided into 25 classes for each rock type.

Several observations can be made from Figure 4.2. Parts c and d show that the Arch and Local components are present at most sites, and in highly variable concentrations. The two components have very similar concentration distributions, suggesting that they are, in fact, from the same population. This observation is consistent with the difficulties in distinguishing between the two components, as mentioned in the previous chapter. The

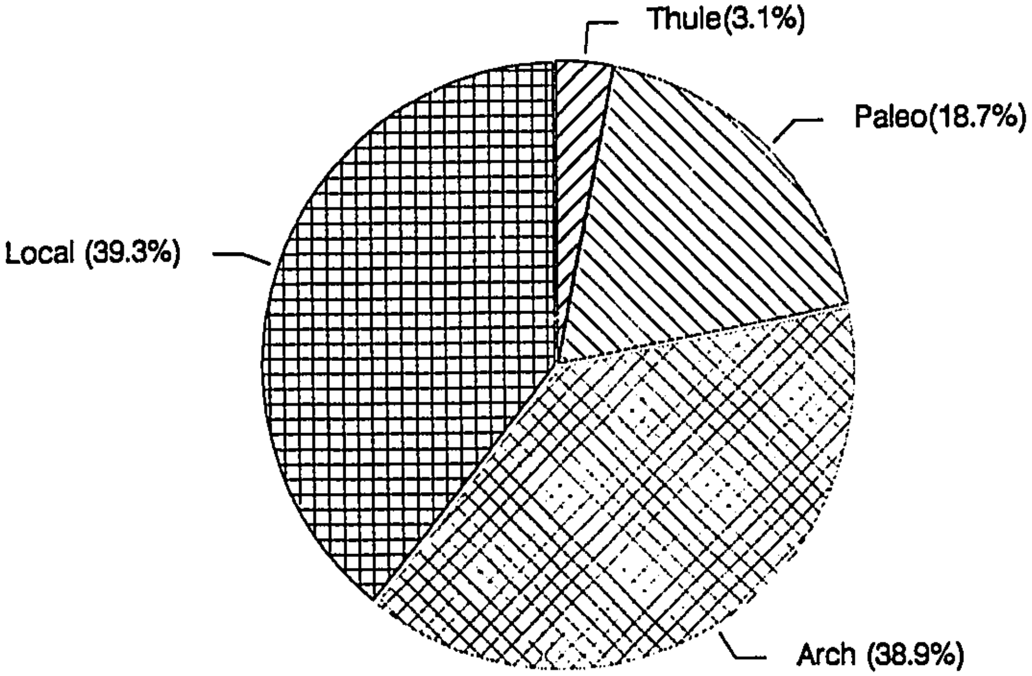

Figure 4.1 Pie diagram showing average composition of tills in the study area in terms of the 4 major components. The proportion of each component was calculated as the sum of the stones of that component at all sites and expressed as a percentage of the total number of stones of all types.

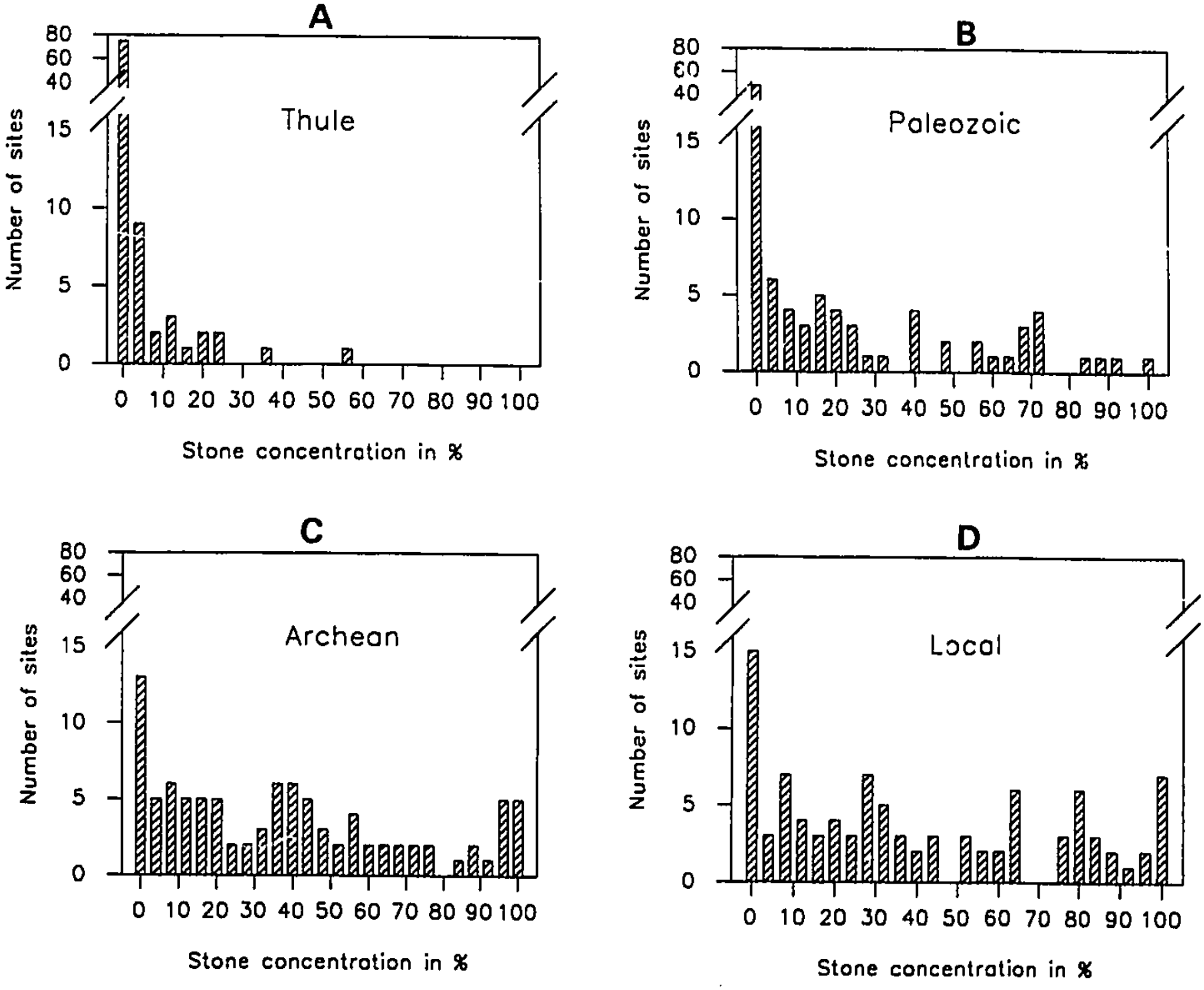

Figure 4.2 Bar graph for each of the 4 components in the tills in the study area showing variation in the concentration of each component among the sample sites. a) Thule erratics are found at few sites and in low concentrations. b) Paleo erratics are found at more sites and in greater concentrations than the Thule erratics. c) and d) Arch and Local components are present at most sites, and in highly variable concentrations.

very uniform concentration distributions of the Arch and Local components suggest that any stone concentration can be found at a given site with approximately equal probability (with a very slightly greater probability of not finding any stone). Figure 4.2a indicates that the Thule erratics are found at few sites and at low concentrations. The Paleo erratics (Fig. 4.2b) are found at more sites and in greater concentrations than the Thule erratics. These results reflect the more restricted areas of outcrop of Thule and Paleozoic rocks in contrast to Archean rocks. From these observations, it can be argued that the Arch and Local components are very poor former glacial flow indicators, compared to the Thule and Paleo components.

4.1.2 Till Classification

The large number of sites makes it difficult to classify the tills in terms of their composition using the raw data. Therefore, the sites must be grouped into a smaller number of categories, each with similar till composition. This can be accomplished by a disjunctive coding method based on isopopulations, which indicates the relationships between rock types. The particular method used here is described in detail in Escofier and Pagès (1988); it can be summarized as follows. The total number of sites (the total sample population) is divided into a predetermined number of classes of approximately equal size (isopopulations). In this case the total population was divided arbitrarily into 5 isopopulations, corresponding to a target of 19 sites per isopopulation. Theoretically, for a given component, the 19 sites with the lowest stone counts would be included in the first class, the 19 sites with the next lowest counts would be in the next class, and so on. In practice, the isopopulation target size is seldom achieved because sites with equal number of stones for individual components must be included in the same isopopulation. For example, 60 of the 96 sites have no Thule component and, therefore, must be put into a single class. Because of the different stone count distributions for the different components (Figure 4.2), the interval sizes and limits for each class will vary. The class limits, the names, and the number of sites are given in Table 4.1.

Using these classes, a table of frequencies was constructed (Table 4.2) which shows the number of sites common to any 2 of the 18 classes minus the number of sites expected for the particular class combination. For each class combination, the expected frequency was calculated as the product of the class sizes divided by the total number of sites (96). For example, there are 30 sites which have no Paleo or Thule components. There are 60 sites from which Thule erratics alone are absent and 34 sites from which Paleo erratics alone are absent. Based on these class sizes, 22% of the sites (= $[60 \times 34] / [96]^2$) are expected to have no Thule or Paleo components. If there are 22 observed sites per 100 sites, there are 21 observed sites per 96 sites. These are 9 more sites (30 minus 21) than expected (cf. Fig. 4.2). Examining the sub-matrices individually, the following observations can be made:

The Arch and Local components did not show any strong relationships with the other rock types except for the combination Local L - Paleo H, which showed 7 more sites than expected. The sub-matrix comparing Arch and Local components associates high and very high values of one rock type with low and very low values, respectively, of the other type. This 'inverse proportionality' suggests that the two rock types are, in fact, part of the same population. The Paleo and Thule sub-matrix shows that both rock types were absent from 9 more sites than expected. These observations support the findings from Figure 4.2: Arch and Local components are poor indicators of ice flow direction, whereas the Paleo and Thule components are better indicators. Based on these observations, Thule and Paleo components were given priority over Arch and Local components (first Thule and then Paleo) when dividing the samples into five till types with different characteristics (Appendix B). Since locally-derived material could unavoidably be mistaken for glacially-transported material identical to the bedrock, no distinction in terms of priority was made between Arch and Local components for the purpose of grouping the classes.

Component	Limits of Class	Description	No. sites in class
Paleo	0	absent (A)	34
	1 to 4	very low (VL)	17
	5 to 22	low (L)	13
	23 to 61	moderate (M)	16
	62 to 180	high (H)	16
Arch	0 to 12	very low (VL)*	24
	13 to 30	low (L)	18
	31 to 54	moderate (M)	16
	55 to 90	high (H)	19
	91 to 158	very high (VH)	19
Local	0 to 9	very low (VL)*	20
	10 to 30	low (L)	16
	31 to 57	moderate (M)	23
	58 to 93	high (H)	17
	94 to 130	very high (VH)	20
Thule	0	absent (A)	60
	1 to 5	very low (VL)	21
	6 to 72	low (L)	15

*includes sites in which the component is absent

Table 4.1 Division of 4 components into 18 classes; the limits (in terms of numbers of pebbles per site) and number of sites are shown for each class.

			Paleo					Arch					Local				
		CLASS	A	VL	L	M	H	VL	L	M	H	VH	VL	L	M	H	VH
	CLASS	Total no. sites	34	17	13	16	16	24	18	16	19	19	20	16	23	17	20
Arch	VL	24	0	-1	-1	-3	5										
	L	18	-2	1	-1	2	1										
	M	16	-3	1	1	0	-1										
	H	19	0	0	0	2	-2										
	VH	19	3	0	1	-1	-3										
Local	VL	20	0	-2	1	0	0	-4	-2	1	-3	8					
	L	16	-2	-2	-2	-2	7	3	0	-3	0	0					
	M	23	-2	-2	2	4	-2	-5	-1	1	6	-2					
	H	17	0	4	-1	0	-3	-2	2	3	0	-2					
	VH	20	4	1	0	-2	-3	8	1	-2	-3	-4					
Thule	A	60	9	4	-3	-5	-5	0	-1	-3	0	4	-1	-1	-3	1	4
	VL	21	-6	-2	2	2	5	2	1	1	-1	-2	0	2	-1	0	0
	L	15	-2	-3	1	4	1	-2	0	3	1	-2	1	-1	4	-2	-3

Table 4.2 Table of frequencies showing the number of observed sites common to any 2 of the 18 classes minus the number of sites expected for the particular class combination; A - absent, VL - very low (for the rock groups Arch and Local, this class includes sites where they are absent), L - low, M - moderate, H- high.

The average compositions of these 5 till types are shown in pie charts (Fig. 4.3) and the compositions of individual samples are shown on the ternary diagram of Figure 4.4. For till type A, the Thule component is low, making the 4 components almost equal in proportion. This till type comprises 15 samples. For till type B, the Thule component is very low in proportion, making up less than 2% of the 21 samples, with the other 3 components being divided up more or less equally. The Thule component is absent altogether from till type C, the Paleo component is variable, comprising almost half of the stones in the 13 samples; the Local and Arch components each comprise about one quarter. For till type D, the Paleo component ranges from very low to absent and comprises less than 2% of the 17 samples; the Arch and Local components each comprise almost half. Finally, the 30 samples in till type E are composed almost equally of Arch and Local components.

The locations of the samples belonging to these till types are shown in Figures 4.5a to 4.5e. The following is a detailed discussion of the spatial distribution of the 5 till types and of the directions of former glacial flow they imply.

The first 3 till types will be discussed together, since they include important Thule and/or Paleo components, the two critical erratic rock types. In terms of their provenance, these three tills fall into one of three categories:

i) Tills at sites that are near Paleozoic and/or Thule Group outcrops, including the tip of Knud Peninsula, southeastern Bache Peninsula, Wade, Gale and Stanfield Points. Paleozoic erratics on Bache Peninsula can be explained by glaciers draining south into Buchanan Bay. The existence of these small outlet glaciers is indicated by northeast-southwest trending striae (Fig. 1.5). For the site at Alexandra fiord, Paleozoic outcrops within 1 km explain the Paleo component in the till. The Thule component is more difficult to explain, as it is not mapped in the area, however, there is always the possiblity of a hidden outcrop under the nearby icecap. It can be noted that for sites at Cape Camperdown, Stanfield and Gale points, Thule erratics are low in proportion and Paleo erratics are absent (these 3 sites could almost

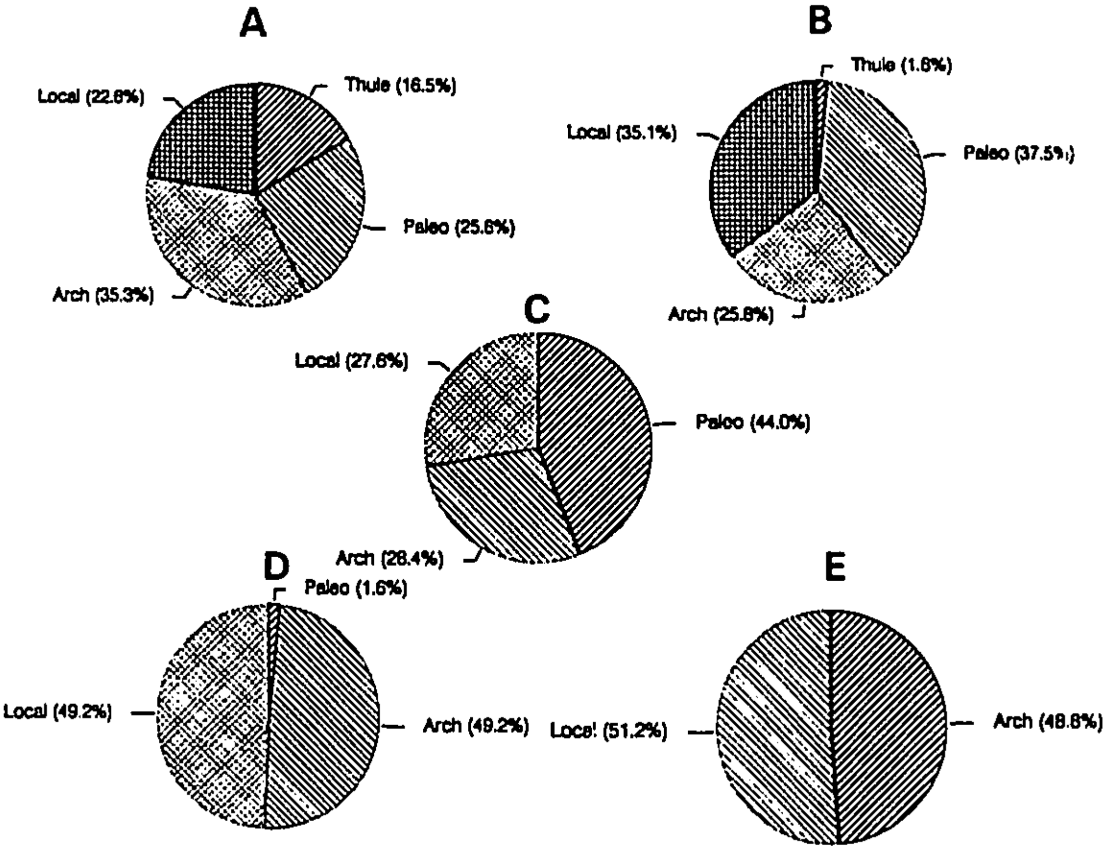

Figure 4.3 Pie diagrams showing average percentages of components in the till types (A to E) in the study area. See explanation in text on previous page.

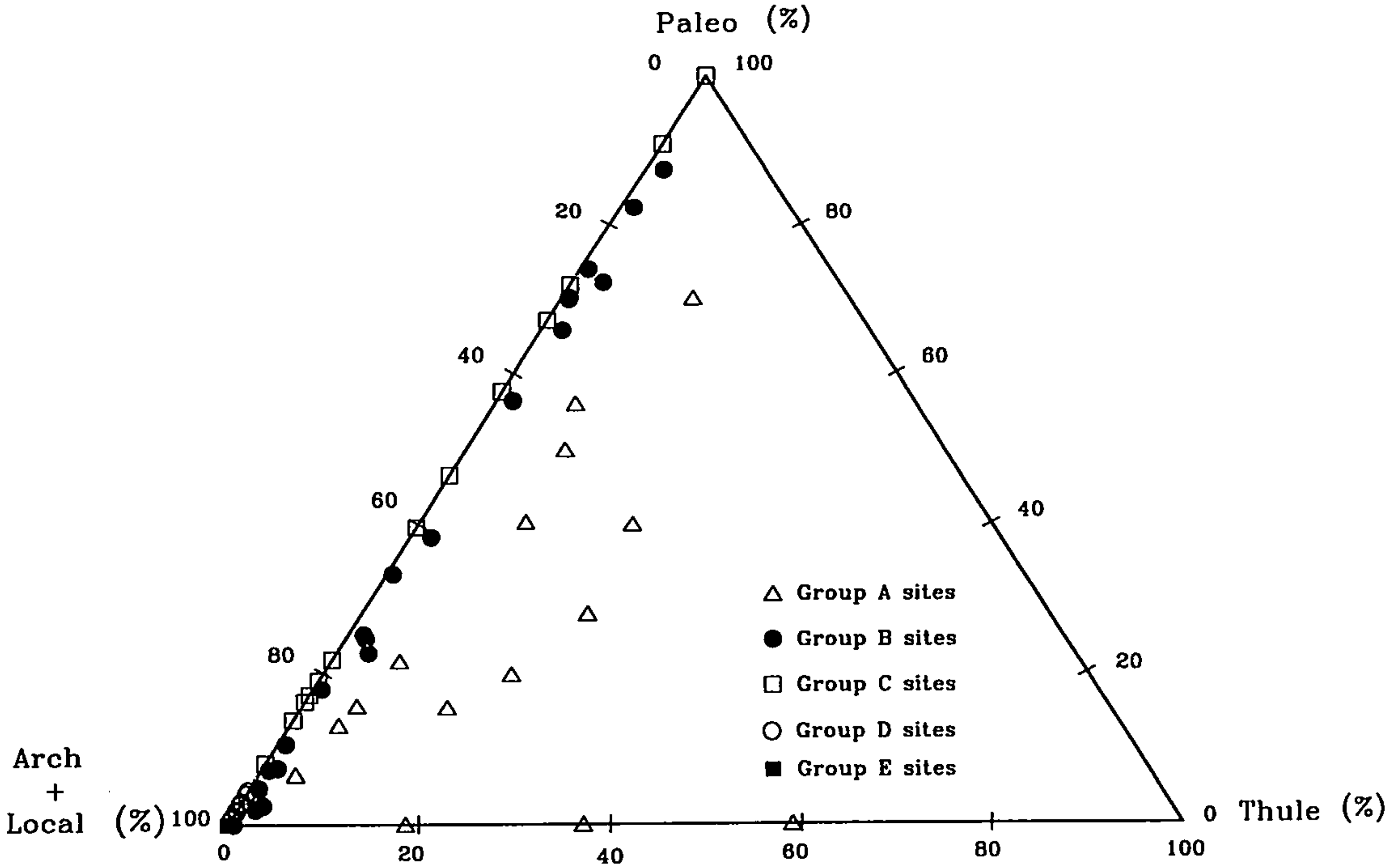

Figure 4.4 Composition of samples in till types A to E plotted on a ternary diagram showing the percentage of Thule, Paleo and Arch + Local components.

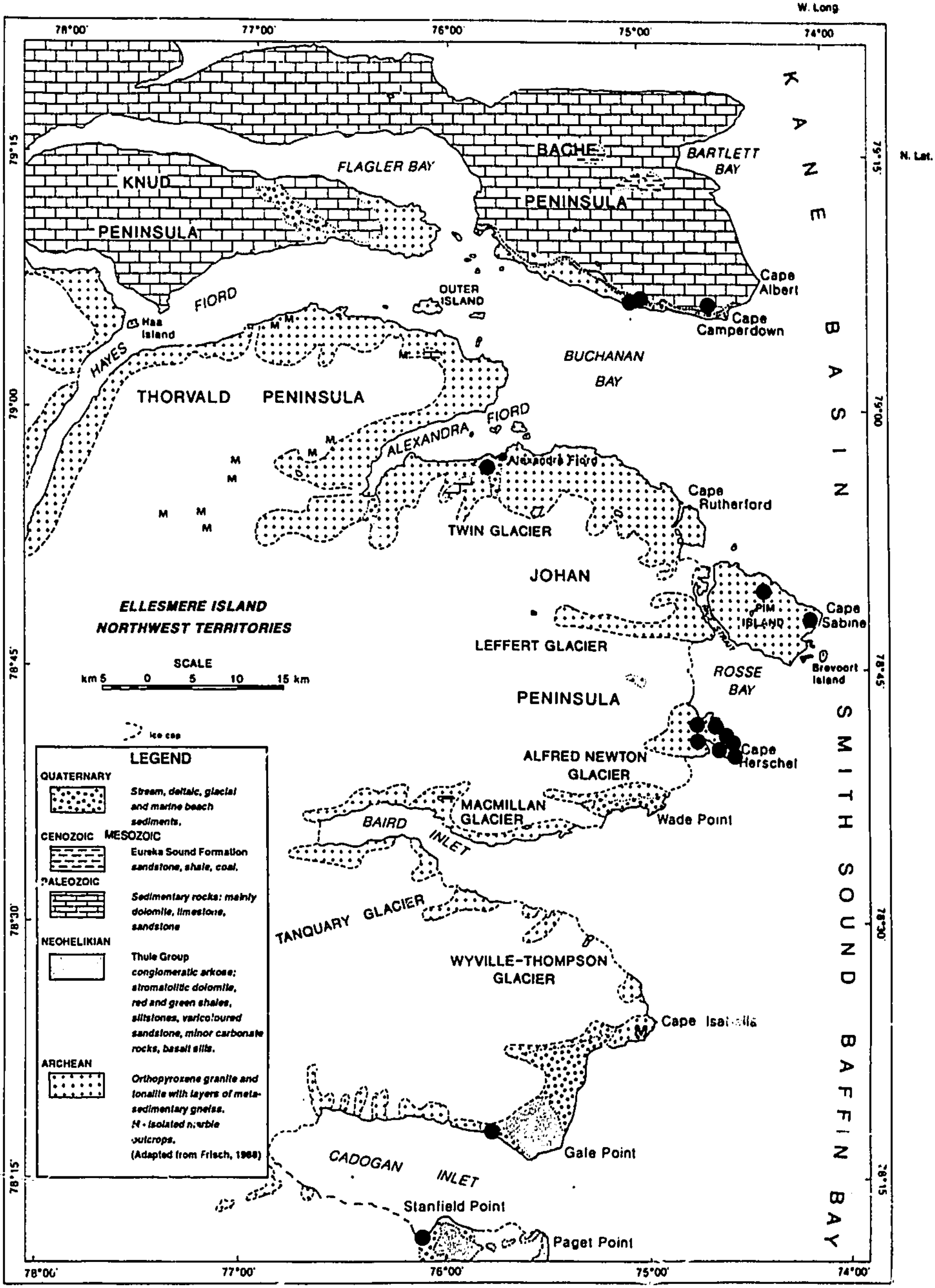

Figure 4.5a Map showing distribution of sites (solid circles) with stone counts included in till type A.

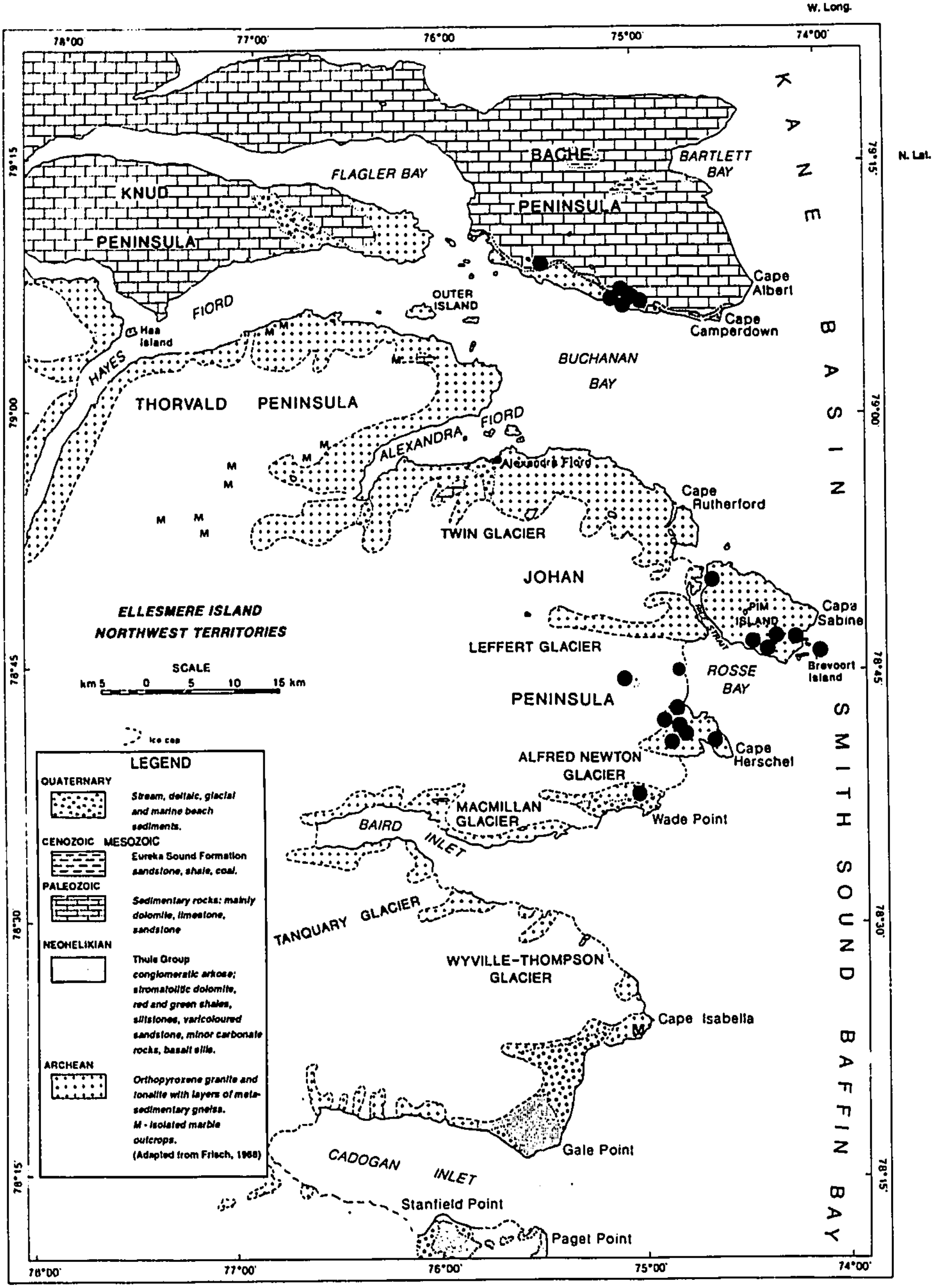

Figure 4.5b Map showing distribution of sites (solid circles) with stone counts included in till type B.

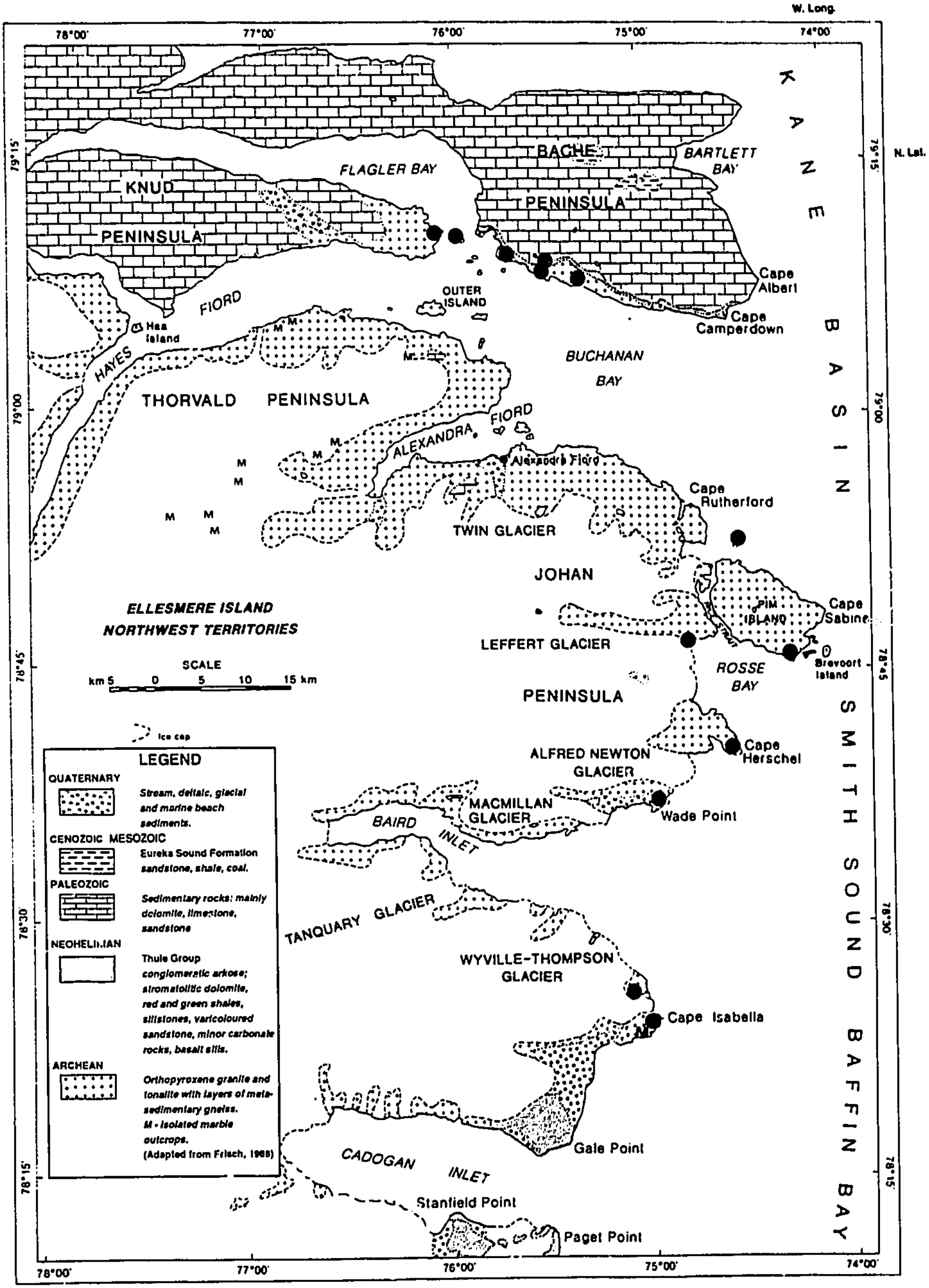

Figure 4.5c Map showing distribution of sites (solid circles) with stone counts included in till type C.

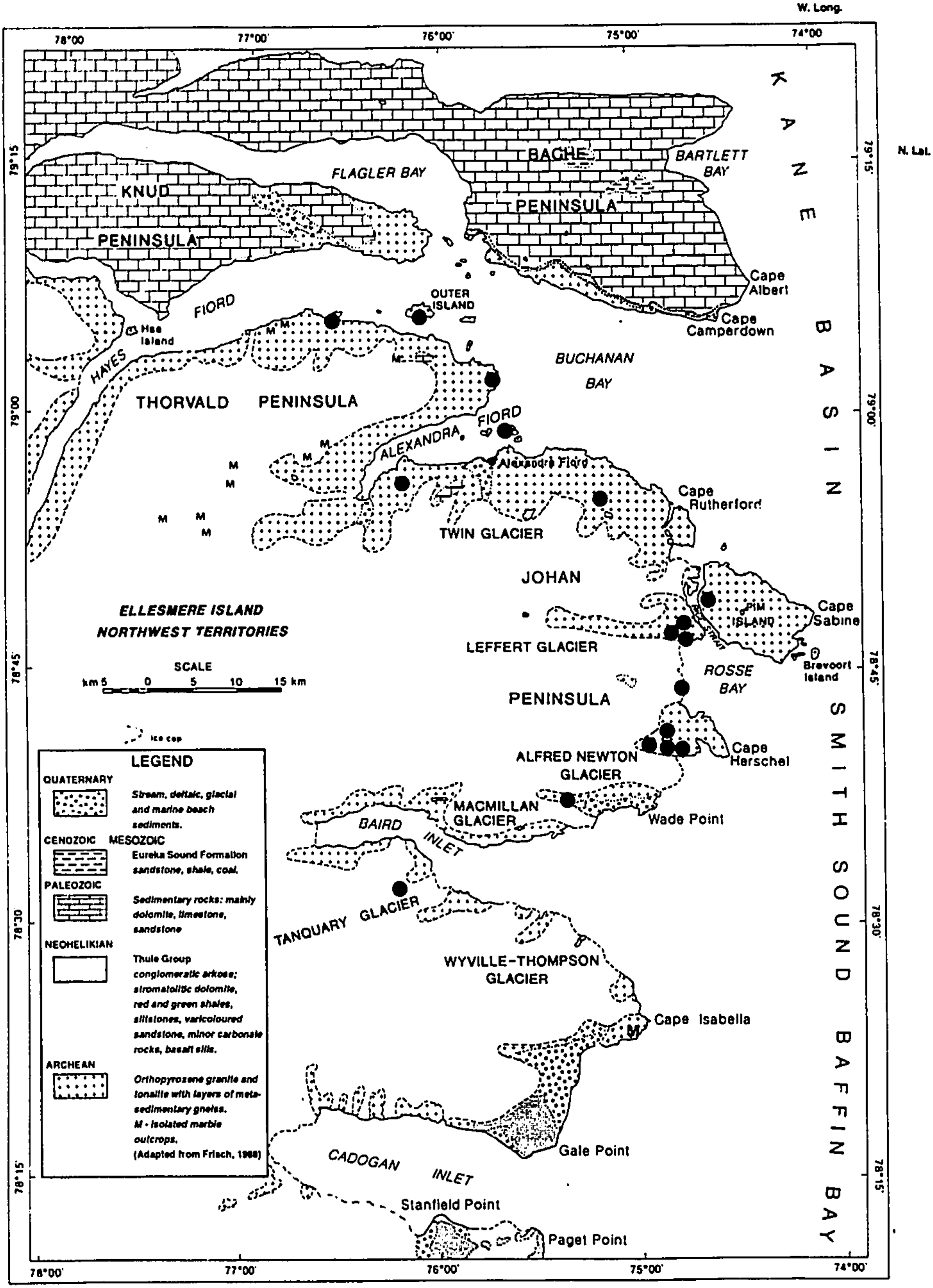

Figure 4.5d Map showing distribution of sites (solid circles) with stone counts included in till type D.

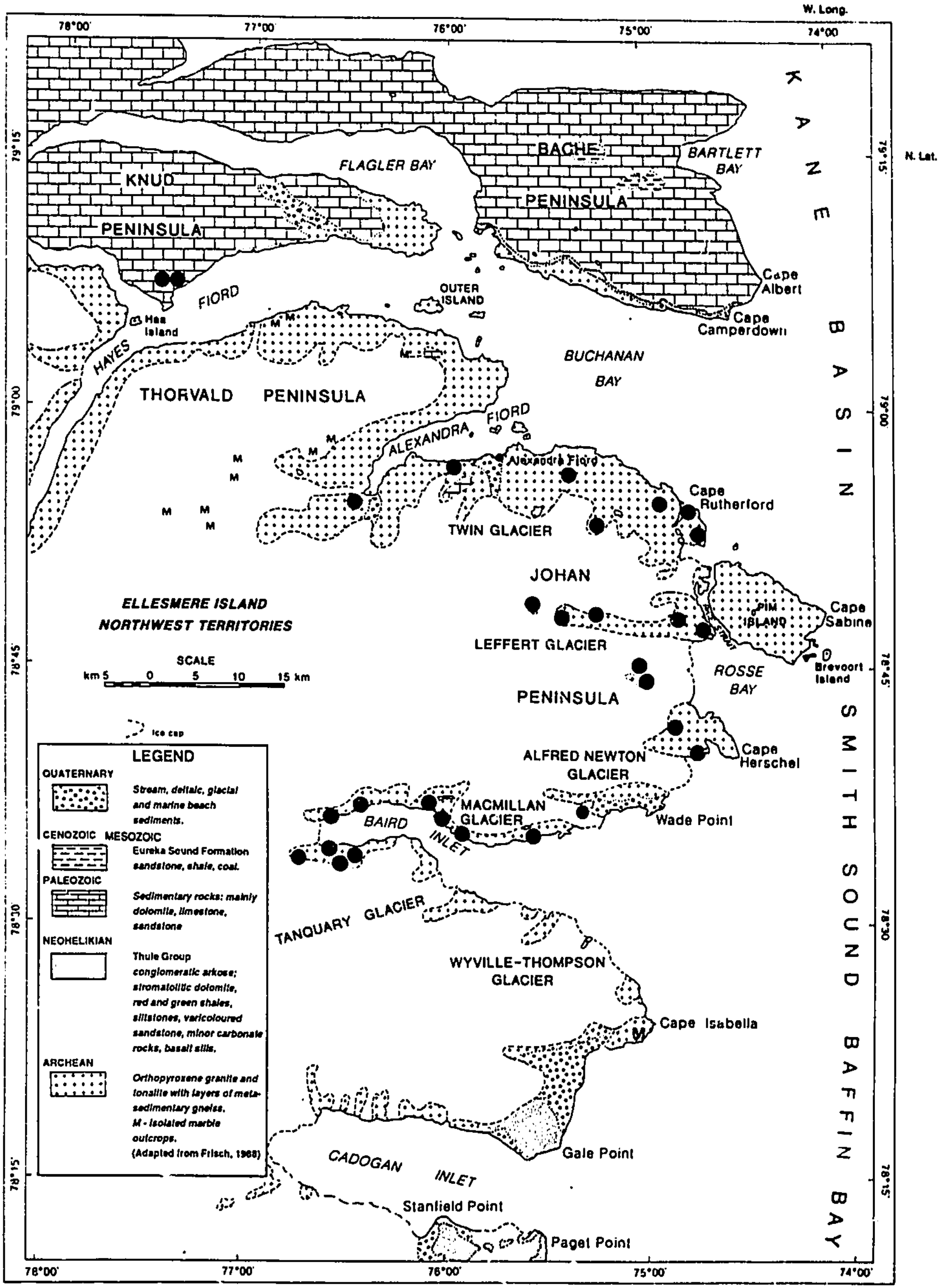

Figure 4.5e Map showing distribution of sites (solid circles) with stone counts included in till type E.

be considered as a separate group). At all three sites, the Thule Group outcrops in close proximity. At Stanfield and Gale points, Paleozoic rocks do not outcrop nearby.

ii) Tills at sites that are in close proximity to present-day glaciers, such as the till type B sites west of Rosse Bay. The Thule component present at these sites is most probably derived from bedrock sources hidden beneath present-day ice. It can be noted that the Thule component is very small at these sites, in contrast to the till type A sites at Cape Herschel.

iii) Tills at the remaining sites have important Thule and/or Paleo components and includes sites on Cocked Hat and Brevoort islands, Pim Island, all the sites on Cape Herschel, 7 of the 11 sites west of Cape Herschel and both sites at Cape Isabella. Of the sites on Pim Island and Cape Herschel, all but two contain both Thule and Paleo erratics (one on the southern tip of Pim Island and the other on southern Cape Herschel, from which Thule erratics are absent). This is the most important sub-group, since the striae and sculpture in these areas indicate north-to-south flow (Blake, 1977), suggesting that the Paleo and Thule erratics have their origins 40 km to the north, on Bache Peninsula. Stone counts on the Precambrian bedrock of Pim Island and Cape Herschel have concentrations of Thule and Paleo eratics similar to those in close proximity to the outcrop area of these two rock units on Bache Peninsula, indicating probable origin. The two sites on Wade Point, six kilometres south of Cape Herschel, have a Paleo component, which also suggests a north-to-south flow. This evidence is supported by a long thin band of till (approximately 10 m across) trending parallel to the outer coast, resembling a lateral moraine. The possibility that north-to-south glacier flow extended as far as Cape Isabella is indicated by the Paleo component in the till. Unfortunately, no sculpture or striae were observed at either Wade Point or Cape Isabella.

The distributions of till types D and E differ significantly from the first three groups in that they comprise the sites the furthest inland (i.e. in Baird Inlet, Hayes and Alexandra fiords). The distribution of these sites clearly indicates former glacial flow from west to east out of the fiords, at the heads of which glaciers exist today. The lack or very small amount of Paleo erratics and complete lack of Thule erratics at both sites on Cape Rutherford, and all 6 sites near the shores of Rice Strait indicate that the same southward-flowing ice which deposited Thule and Paleo erratics on Pim Island did not penetrate further west in this area. Similarly, the 7 sites west of Cape Herschel appear to have been practically unaffected by southward-flowing ice. Other sites included in these two groups are situated on nunataks or in very close proximity to present-day glaciers, reflecting the composition of the almost exclusively Archean nature of hidden bedrock in these areas.

The major flow directions were confirmed using a multivariate statistical method. Principal component analysis is useful in correlating more than 2 or 3 variables at one time. It is ideal in this case, in which 4 lithological variables are involved. The method consists of determining the eigen values and vectors (i.e. the principal directions) of the covariance matrix. Thus, the analysis extracts the strongest tendencies, puts them in a hierarchy and at the same time eliminates the marginal effects that perturb the global perception of the principal tendencies. In this study, it can be used to identify tills of similar composition. The method uses classes based on isopopulations (such as shown in Table 4.1) following Escofier and Pagès (1988).

The results of principal component analysis produce groupings of the sites similar to those shown in Figures 4.5a to 4.5e. One group of sites, characterized by large amounts of Paleo and Thule is found along the outer coast, including many of the sites in the Pim Island - Cape Herschel area. North-to-south flow is implied by these results given that the largest outcrops of Thule Group and Paleozoic rocks are on Bache Peninsula. A second group characterized by large amounts of Arch and Local components and minor amounts of Thule and Paleo components includes sites located in the interiors of the fiords. The composition of the till, which reflects the local bedrock, indicates west-to-east flow out of the fiords. This is consistent with the location of present-day glaciers. Details of the results of factor analysis are discussed in Appendix F.

4.2 Geochemistry

The results of the geochemical analyses are given in Appendix C. In the case of molybdenum, amounts analysed as being less than 1 ppm were given the value of 1 ppm.

The following observations can be made regarding the spatial distribution of the 6 elements:

Factor and principal component analyses performed on the geochemical data revealed no significant relationship between geochemical components. In general, the scarcity of the data points make it difficult to interpret the geochemical data. It is possible that Co, Cr, Cu, Mn, and Fe are components of the numerous types of Archean crystalline basement rocks which outcrop in the lower nine-tenths of the study area. However, because the outcrops of each rock type are numerous and sporadic throughout the study area, it is impossible to relate an element to a single rock type.

The concentration of geochemical elements can be compared to those from a similar geological setting. Kettles (1992) carried out a study of glacial sediment geochemistry in The Clyde Forks - Westport area in Ontario. The eastern half of the study region is underlain by Paleozoic clastics and carbonates which lie within the Central St. Lawrence Lowlands. The western half of the study area is underlain by Proterozoic rocks of the Central Metasedimentary Belt of the Grenville Province. The till is generally thin (<1.5 m) and discontinuous. The predominant ice-flow direction, as evidenced by the orientation of striae and drumlins, was south-southwestward. The <2 μm fraction of 520 samples of drift (predominantly till) was analysed for Cu, Fe, Mo, Mn, Co, and Cr (among other elements). The range of concentrations is as follows: Cu -- 55 to 1115 ppm, Fe --1.2 to 32.5%, Mo -- 1 to 20 ppm, Co -- 3 to 186 ppm, Mn -- 60 to 12,000 ppm, and Cr -- 20 to 245 ppm.

In this study, two samples have extremely high concentrations of Cu -- on northern Pim Island (880 ppm) and on Cocked Hat Island (1905 ppm). These elevated concentrations of Cu are probably related to Cu mineralizations mapped by Frisch (1988) in the northern part of the study area, on the eastern tip of Knud Peninsula, northern Thorvald Peninsula, Outer Island and northern Johan Peninsula.

In addition to high Cu concentrations, the amounts of Fe, Mo and Co in the study area are considered to be elevated compared to other Canadian Shield tills (W. Shilts, personal communication). For example, 4 sites have Fe concentrations over 8% -- on Pim Island (9.1%), Cocked Hat Island (12.2%), Cape Rutherford (17.8%), and 10 km west of Cape Rutherford (13.6%). Seven sites, located throughout the study area, have Mo concentrations over 5 ppm. The Co concentrations range from 4 to 77 ppm, also considered to be unusually high for Canadian Shield tills (W. Shilts, personal communication). No Fe, Mo or Co mineralizations have been mapped in the study area by Frisch (1988).

Concentrations of Mn (200 to 3,300 ppm) and Cr (27 to 190 ppm) in the study area are within the range of the Clyde Forks - Westport tills (published in Kettles, 1992).

4.3 Granulometry

The percentages of sand (2000 to 63 μm), silt (63 to 2 μm) and clay (<2 μm) for the tills corresponding to the 95 pebble count sites are listed in Appendix D. The tills have a large percentage of sand (43.05 to 97.38%), with a much lesser proportion of silt (1.65 to 34.73%) and even smaller component of clay (1.63 to 18.35%).

Sand/silt/clay components for 95 till samples are plotted on a ternary diagram, Figure 4.6. Tills of different provenance would appear as clusters of points with approximately the same composition of sand, silt and clay. One might expect to be able to identify the clusters of tills representing the various fiords, but although the points are somewhat dispersed (with 3 isolated points), no distinct groups can be distinguished (cf. Fig. 2.4a and 2.4b).

According to Scott (1976), Canadian Shield Province tills are "generally non-calcareous, coarse-grained and have a low content of clay-size particles". In the study by Kettles (1992), described in the preceding section, glacial sediments were found to be

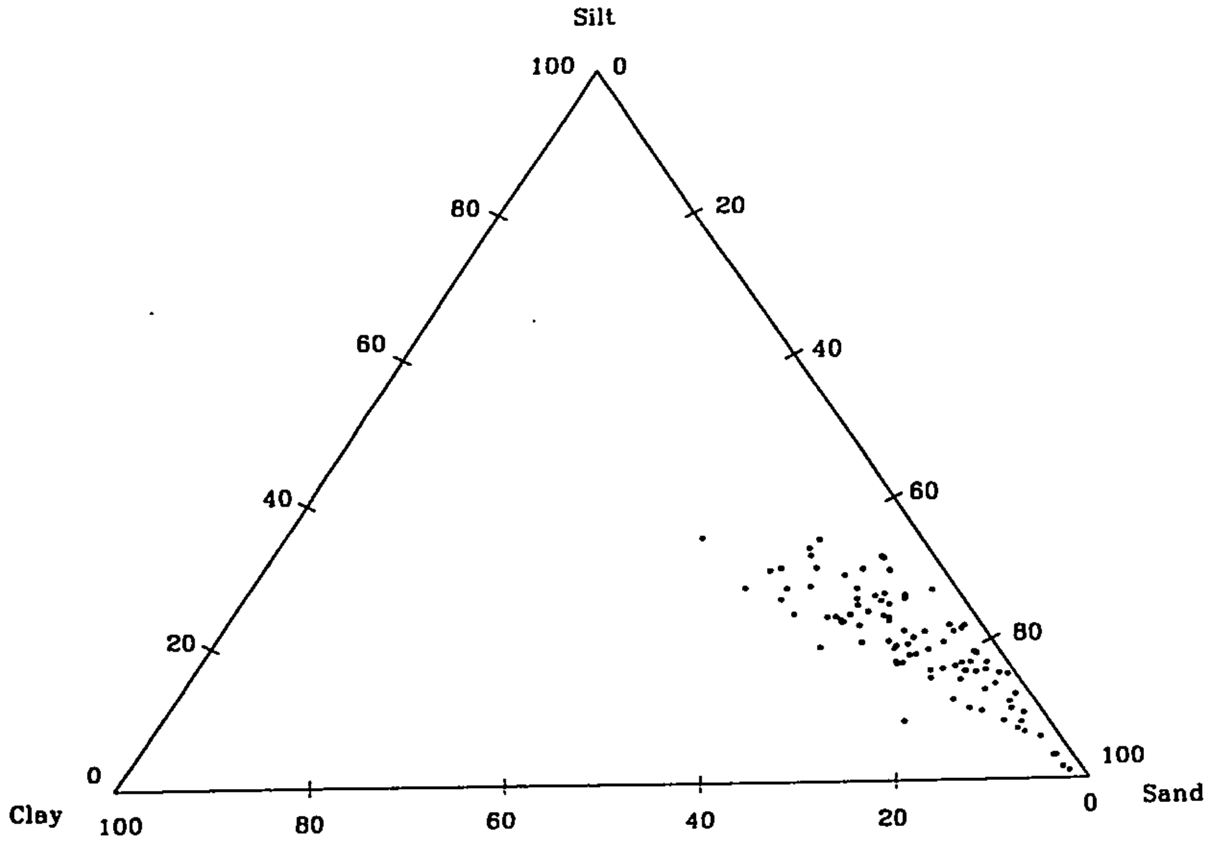

Figure 4.6 Granulometry of 95 till samples in the study area plotted on a ternary diagram. Clusters of points cannot be distinguished.

enriched in silt plus clay-sized carbonate over Paleozoic terrane and over the area of Canadian Shield terrane west and southwest of the Paleozoic-Precambrian boundary, where glacial sediments had high concentrations of Paleozoic clasts. The till in these areas are also generally more fine-grained. To the west, outside of the area of Paleozoic carbonate enrichment, the sand content in the matrix of Sheild till is generally greater than 75%. Overall in the study area, the clay (<4 µm) varies from 0.6 to 39.5%, the silt (<63 µm to >4 µm) from 3.8 to 53.3% and the sand (<2 µm to >63 µm) from 7.4 to 95.6%.

The higher component of clay found in the tills on east-central Ellesmere Island compared to other Canadian Shield Province tills (W. Shilts, personal communication) may be the result of the incorporation of unconsolidated marine sediments. Arctic Platform rocks, which outcrop in the north of the study area, may also have been a source of silt- and clay-sized material.

4.4 Munsell Colours

With few exceptions, the till in the study area varies from grey to brown, with numerous hues and intensities (see Appendix E for raw data). Altogether, 25 different Munsell colours were identified. These 25 classes are shown on a bar graph grouped according to their hue (the first number; Fig. 4.7). By far, the two most prominent colours are light brownish grey (2.5Y6/2) and greyish brown (2.5Y5/2), which account for 14 samples each (or 18% each of the total). The remaining samples fall into one of 23 classes, 12 of which have only one sample.

It should be pointed out that there was considerable colour variation even between tills sampled within 10 m of each other. For example, at site 82, on the north side of Hayes Fiord, one till was light brownish grey (2.5Y6/2), while another close by was light olive grey (5Y6/2). However, most of the tills can be classified as either brown or grey (which are possibly different tills) or some combination of the two.

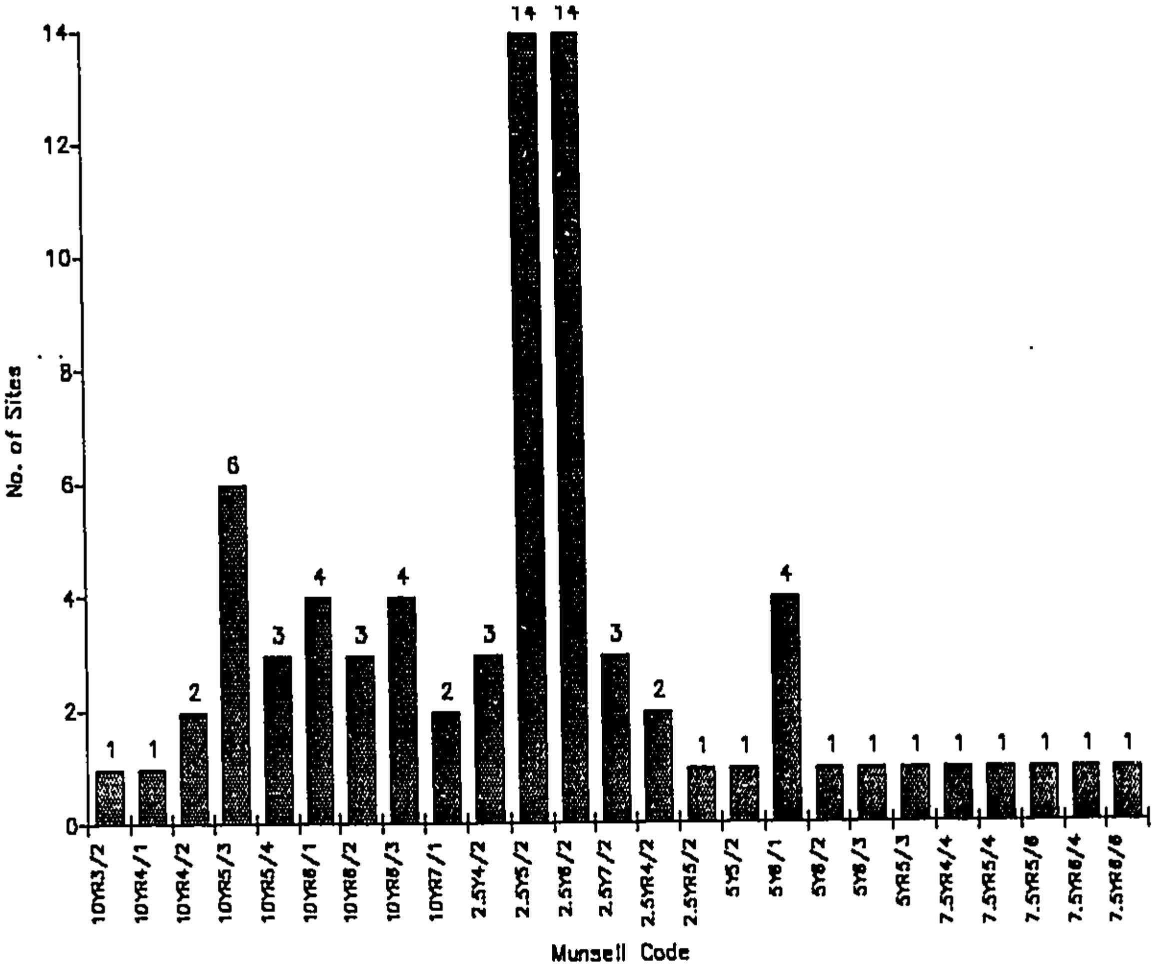

Figure 4.7 Frequency histogram representing Munsell colours of 76 tills in the study area. Twenty five classes are represented (see Annex E for explanation of codes). The two prominent colours are light brownish grey (2.5Y6/2) and greyish brown (2.5Y5/2).

In order to simplify the representation of the spatial distribution of Munsell colours, the colours were divided into a smaller number of groups, according to their colour description in the Munsell chart (e.g., greyish brown etc.). Since brown and grey are the prominent colours, the following groups were chosen: i) brown (including the variations pale, strong, light, yellowish and reddish), ii) grey (including the variations dark, light, and olive), iii) intermediate colours between brown and grey (light brownish grey, greyish brown etc.), iv) weak red v) reddish yellow, and vi) pale olive.

These 6 groups comprise 18, 16, 37, 3, 1 and 1 sample(s), respectively (see Appendix E for a complete listing). From the distribution of these colour groups in the study area (Fig. 4.8), the following comments can be made:

Brown tills are distributed from the north to the south of the study area, with a small cluster of 4 points on Bache Peninsula. Comparing these sites to the bedrock geology, it can be seen that in numerous instances, the brown till is associated with red-brown granitic bedrock (sites 15, 16, 19, 23, 25, 31, 35, 55 64, 70, 71, 84, 85, 88, 89, 90).

Comparing the grey till sites to the bedrock geology, it can be noted that the grey tills are often found within close proximity to light-coloured Paleozeoic bedrock. Site 91 is on Paleozoic bedrock and Paleozoic bedrock outcropped within a few tens of metres of site 93. Grey tills at sites on granitic bedrock but in very close proximity to present-day glaciers (sites 41, 49 and 52) indicate the possible presence of Paleozoic rocks under the ice cap.

Grey/brown tills are also widely distributed throughout the study area but there is a concentration in the the Pim Island - Cape Herschel area. This may reflect the presence of light-coloured Paleozoic glacial debris in what would otherwise be a brown till.

The two weak red tills can probably be grouped with the brown or grey/brown tills, since they were collected on the Pre-Cambrian granites of Bache Peninsula. The uniqueness the pale olive till on Cape Rutherford and the reddish yellow till near Alexandra Fiord are probably the result of a local anomalous outcrop.

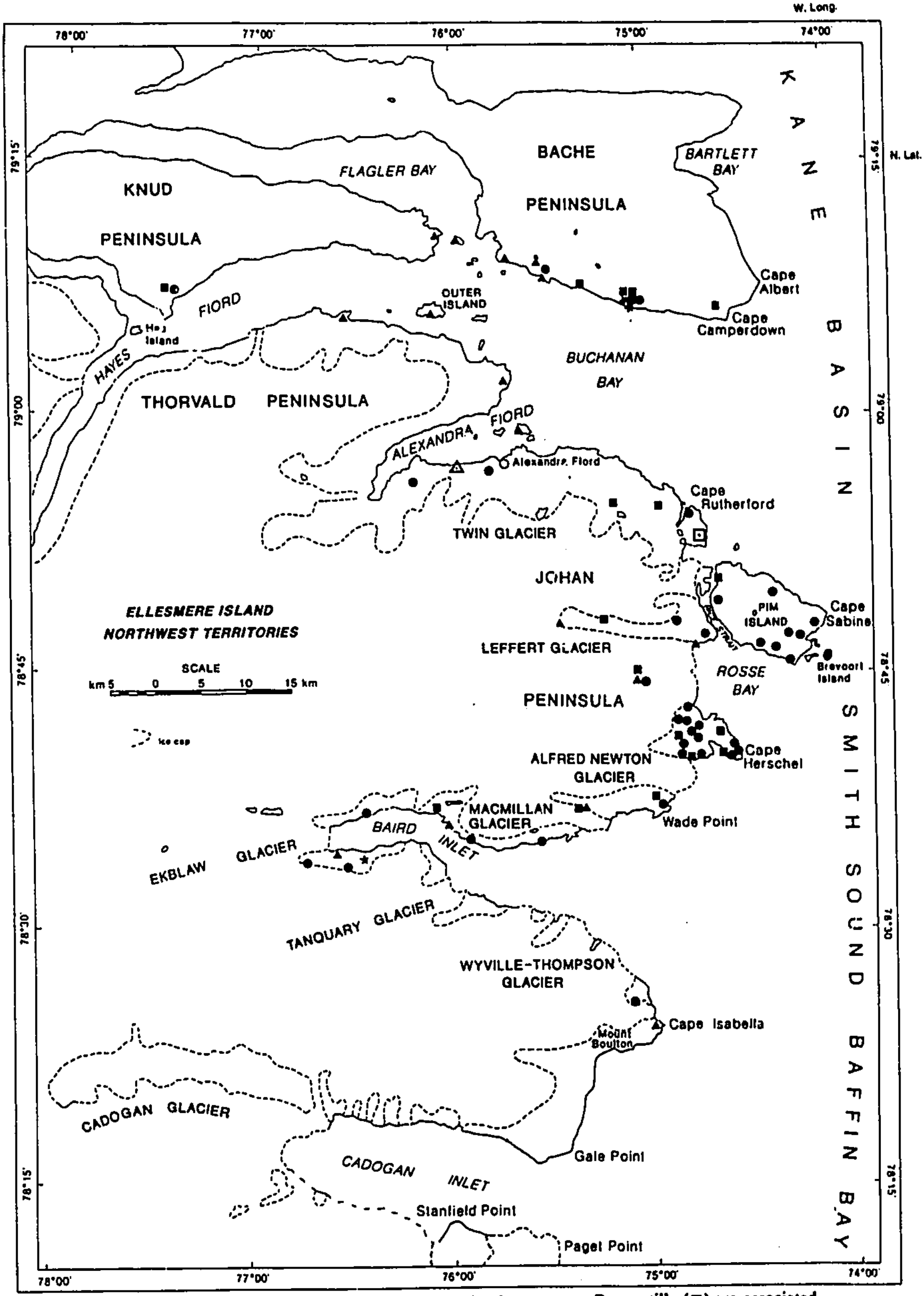

Figure 4.8 Map showing distribution of till colour groups. Brown tills (■) are associated with Archean bedrock, grey tills (▲) with Paleozoic bedrock; grey-brown till (●) represents a large Paleozoic component of till on granitic bedrock. The other three tills colours are weak red (★), pale olive (△) and reddish yellow (□).

In conclusion, the most interesting result of the Munsell colour maps is the presence of grey/brown tills in the Cape Herschel - Pim Island area. If, indeed, the grey/brown colour reflects a high amount of Paleozoic material in the till (which is supported by the results of the stone counts), the closest known source is 40 km to the north on Bache Peninsula.

5. RECONSTRUCTION OF LATE QUATERNARY ICE FLOW DIRECTIONS

The purpose of provenance studies is to determine former directions of glacial flow, which explains their widespread application to prospecting in formerly glaciated terrain. Aside from these uses, they are also an aid in the assessment of the paleoclimatic and chronostratigraphic interpretations of high latitude ice cores and the delimitation of Pleistocene refugia. However, the accuracy of the provenance studies are highly dependent on the sampling techniques used, in particular on the depth and density of sampling. Ideally, unweathered samples are collected at depth in a grid pattern. In this study, however, several limitations were imposed by the physical nature of the study area.

Most of the study area is covered by large ice caps and water. This has resulted in a very high sampling density over a relatively small part of the total area; sampling over the whole study area might have improved the identification of nuances in paleoflow directions. Another complication arising from the vast ice cover is that the bedrock geology underneath the ice caps remains unknown. Therefore, it is impossible to identify the sources of the erratics in the till with complete certainty.

In ice-free coastal areas, the thin till cover and near-surface permafrost made sampling unweathered till impossible, in most places. As previously discussed in Section 2.3, surface sampling of fines is not recommended due to the problems of leaching, cryoturbation and aeolian input. These processes are known to take place in the study area, indicated by encrustations and efflorescences on the surface of the till, frost boils and wind-transported sediment in the snow. It appears, therefore, that surface sampling was probably in part responsible for the poor geochemical and granulometric results.

Despite these drawbacks, the stone count data, and to a lesser degree, the Munsell colours, indicates two general paleoflow directions in east-central Ellesmere Island: i) from west to east out of the fiords that dissect the interior and ii) from north to south along Nares

Strait, from Bache Peninsula to Cape Isabella (a distance of 60 km). The ice that overrode the outer coast in the area of Pim Island and Cape Herschel was probably cold-based (indicated by the thinness of the till; Scott, 1976).

Before putting the results of this study into a more general context, two major questions need resolution. First, was the till studied related to an expansive ice-sheet as described by Blake (1977) or was it deposited simply by local ice, according to the limited ice model proposed by England (1976a)? Second, during which glacial event was the till in the Cape Herschel - Pim Island area deposited?

Assuming that there was no southward-flowing ice through Smith Sound, the Paleo and Thule erratics in the Pim Island - Cape Herschel area must be accounted for, since the closest outcrop of these two rock groups is 40 km to the north on Bache Peninsula. The lithology of the bedrock underneath the ice sheet is known to be composed of some Paleozoic formations which outcrop as nunataks in the Prince of Wales Ice Cap. Could expanded present-day glaciers, draining southeastward into Kane Basin and Smith Sound have deposited the large amounts of Paleozoic material found in the eastern Pim Island - Cape Herschel area? If this were the case, two problems remain: how can the north-to-south oriented striae and sculpture be explained in the Cape Herschel - Pim Island area and why are there a few Paleo erratics west of Rice Strait, west of Cape Herschel or on most of western Pim Island?

Assuming that the north-to-south-trending striae can be explained by local ice, this would mean that the ice thickness was over 300 m (the elevation of Cape Herschel). The glacial features, however, seem less likely to be the product of local ice. Aside from small roche moutonnées found on Pim Island and Cape Herschel, both sites have plucked lee (south) and rounded stoss (north) sides. Could a spreading tongue of local ice issuing from the Buchanan Bay area advance so far south as to sculpt Pim Island? Could a similar advance in the Leffert Glacier area produce the sculpture on Cape Herschel? Perhaps Pim Island acted as a barrier which pushed Leffert Glacier ice southwest across Cape Herschel.

The scarcity of Paleo erratics west of Cape Herschel and on western Pim Island is impossible to explain assuming an expansion of local ice on Johan Peninsula. Presumably, it would have deposited a fairly homogeneous till as it advanced from west to east.

The observations made in this study cannot easily be explained by assuming that only the expansion of local ice affected the area. Therefore, a working hypothesis is proposed, based on the integration of results of stone counts, geochemistry, Munsell colours and previous observations of striae, glacial features and marble collections. Figure 5.1 summarizes the essential points of this hypothesis.

Following Blake's (1977) theory of an Innuitian ice sheet, outlet glaciers drained ice sheets on both northern Ellesmere Island and northern Greenland, filled Kane Basin and drained southward toward Smith Sound. Further inland in the Flagler Bay area on Ellesmere Island, ice flowing southeastward into Buchanan Bay eroded the southwest corner of Bache Peninsula. A southeastward flow across the Archean bedrock is indicated by well-developed striae and sculptured bedrock. In the Buchanan Bay area, ice was fed by small outlet glaciers on Bache Peninsula draining southward. This is indicated by northeast-southwest trending striae. Till types A, B and C sites (relatively high in Paleo and/or Thule erratics) on southern Bache Peninsula are also evidence of the southward flow since the source rocks for Paleo and Thule erratics outcrop only a few hundred metres to the north.

Ice flowing southeastward out of Buchanan Bay was deflected by ice flowing southwestward out of Kane Basin (100 km across) toward Smith Sound (40 km across). Upon reaching the bottleneck at Smith Sound, Buchanan Bay ice was squeezed around Cape Rutherford and west of Pim Island, which at the same time prevented the Kane Basin ice from forcing its way further west.

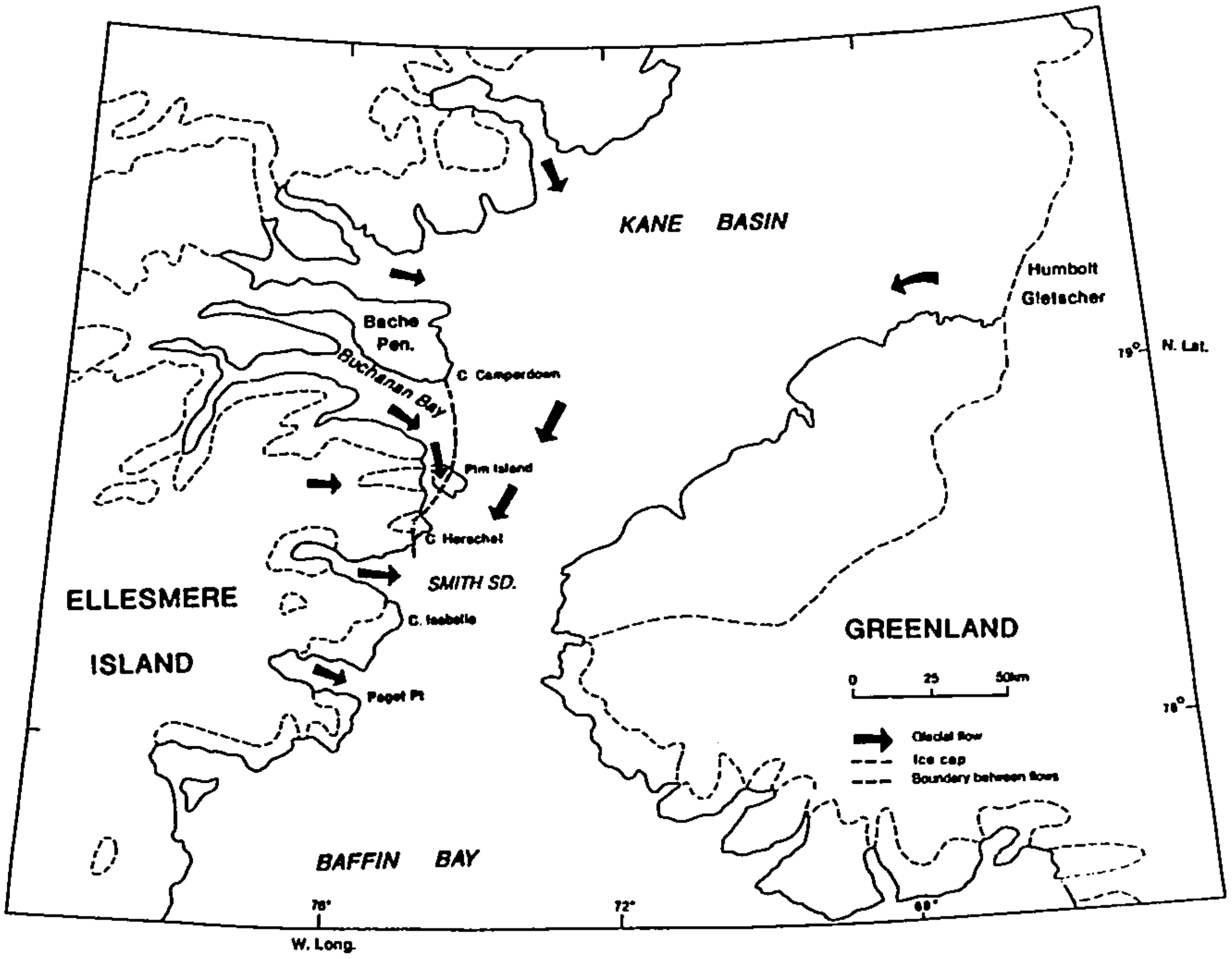

Figure 5.1 Glacial flow directions interpreted from combined evidence of stone counts and Munsell colours (this study) and previous observations of striae and erratic collections made by W. Blake, Jr. Ice flowed from west to east out of the fiords on eastern Ellesmere Island and north to south from Kane Basin through Smith Sound.

If correct, this would account for till types D and E sites (which possess no Thule and zero to low Paleo erratics) on Cape Rutherford and west of Rice Strait and on westernmost Pim Island (site 61). This is because Buchanan Bay ice drained from areas dominantly underlain by Archean bedrock (e.g. Hayes and Alexandra fiords). The small component of Paleo erratics in till type D sites interspersed with till type E sites on westernmost Pim Island (site 61), west of Rice Strait and west of Cape Herschel might therefore be the result of Flagler Bay ice which eroded the southwestern tip of Bache Peninsula before being deflected southward. In contrast, till groups A, B and C sites (relatively high in Paleo and/or Thule erratics) on eastern Pim Island and Brevoort Island, were mostly affected by Kane Basin ice which incorporated Thule and Paleo rocks by eroding the southeastern tip of Bache Peninsula.

The location of four marble erratics found in the study area also support flow from west to east out of the Hayes and Alexandra fiords and then north to south through Rice Strait. A marble erratic found on northern Johan Peninsula, on a ridgetop near the head of Alexandra Fiord, indicates ice flow eastward from the Prince of Wales Mountains through Alexandra Fiord. Marble erratics present on southern Pim Island and on a ridgetop west of Rice Strait (480 m a.s.l.) are most likely to have been derived from Alexandra Fiord or the south side of Hayes Fiord.

South of Pim Island, southward-flowing ice was able to push further west, as indicated by the large component of Thule and Paleo erratics at sites on Cape Herschel Peninsula, implying that some erratics have travelled at least 40 km from their source on Bache Peninsula. Elison Pass, a large through-valley oriented north-south on western Cape Herschel (visible just to the right of the arrow in Plate 1.6, was probably scoured out by the southward-flowing Kane Basin ice. The presence of a marble erratic on the eastern part of the Cape Herschel plateau and till types A and B sites, just west of Cape Herschel, may indicate the extent to which ice draining from Buchanan Bay was able to push west.

South of Cape Herschel, there is less evidence of southward-flowing ice. A long thin band of till (approximately 10 m across) at the top of Wade Point (elevation 230 m a.s.l.), trending parallel to the coast, may represent either a lateral moraine that resulted from southward flow of ice through Smith Sound or a terminal moraine that resulted from expanded present-day ice caps to the west. Although Thule erratics are components in one of the two stone counts at Wade Point (site 19), it is not certain that they were carried south from Bache Peninsula because the Thule Group also outcrops several kilometres to the west of Wade Point. As a result, Thule material could have been deposited by local ice. However, the high component of Paleo erratics at both sites on Wade Point and 20 km to the south at Cape Isabella (where neither Thule nor Paleozoic rocks outcrop) supports southward flow in these areas. The possibility that Paleozoic rocks outcrop present under nearby glaciers cannot be overlooked. Unfortunately, no striae were observed at either location.

In general, the paleoflow directions that are reconstructed using all the available data are in agreement with the conclusions drawn by both Blake (1977) and Christie (1983).

A second major problem concerns the timing of the glacial events. In this respect, no observations have been made to establish clearly the absolute age of the uppermost till(s) in the Queen Elizabeth Islands. The pattern of emergence and the C^{14} derived age dates on marine shells and driftwood, which Blake (1964, 1970, 1972, 1975) proposed as criteria for the presence of the Innuitian Ice Sheet are considered to be inconclusive by England, as no stratigraphic evidence has been found to support an expansive ice model (England, 1976b; Hodgson, 1985). Although the sculpture and striae in the Cape Herschel - Pim Island area have been described as 'fresh-looking' by Blake (1977), the only way to date them is by carrying out an in-depth study of weathering criteria such as silica to alumina weathering ratios, thickness of weathering rinds, amount of differential weathering of dykes, size of micropits or numbers of intensely weathered erratics.

Because there is no firm evidence that the two models need to be concurrent in age, it is possible to reconcile the two conflicting interpretations as follows: an early Innuitian ice sheet existed over northern Ellesmere Island and Greenland but was pre-Wisconsin in age. By contrast, only local ice expansion took place during the last glaciation. This conciliating position accounts for both the features attributed to noncontiguous ice cover in northeastern Ellesmere and northwestern Greenland, as described by England, and the erratics, sculpture and striae on east-central Ellesmere Island, as described by Blake.

Provenance studies alone cannot resolve the problem of the timing of the glacial events in east-central Ellesmere Island. However, more detailed studies would provide greater precision on former flow directions. This could be done by sea sediment sampling in the Smith Sound area (for example in Buchanan and Rosse bays) or by the identification of erratics from tracer beds of very limited outcrop in the northern part of the study area. The latter would require detailed bedrock mapping and would not solve the unavoidable problem that much of the bedrock is unknown, hidden by present-day glaciers. Heavy mineral analysis of the till is another technique that could be attempted.

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APPENDIX A

No. of stones in each lithological group

SAMPLE NO.	THULE	PALEO	ARCH	LOCAL
1	48	0	81	0
2	72	0	50	0
3	0	57	75	12
4	0	31	72	60
5	0	2	80	23
6	0	0	38	114
7	0	0	66	71
8	0	0	0	130
9	0	0	18	30
10	0	0	155	24
11	0	0	53	55
12	0	0	1	130
13	0	0	142	17
14	0	0	158	0
15	0	0	54	91
16	0	1	99	33
17	0	0	133	0
18	0	63	17	14
19	3	139	0	17
20	0	1	119	0
21	0	17	75	32
22	0	1	28	91
23	0	1	7	117
24	0	0	23	88
25	9	23	98	47
26	9	27	54	35
27	1	0	56	106
28	1	20	41	50
29	7	19	64	32
30	20	20	52	38
31	0	1	21	126
32	9	60	29	9
33	0	0	0	96
34	2	2	33	67
35	28	33	49	8
36	1	51	70	31
37	3	3	17	100
38	25	25	41	35
39	2	[illegible]6	49	0
40	0	5	123	0
41	1	5	101	0
42	0	0	78	33

SAMPLE NO.	THULE	PALEO	ARCH	LOCAL
43	3	35	104	0
44	0	0	137	0
45	0	23	13	106
46	1	89	11	26
47	0	19	92	0
48	0	1	135	0
49	0	6	131	0
50	1	12	7	95
51	4	27	20	68
52	0	0	85	52
53	0	2	40	74
54	0	0	103	50
55	0	0	1	126
56	2	9	13	100
57	3	50	12	66
58	0	0	5	109
59	0	0	67	55
60	16	58	20	50
61	0	1	58	76
62	38	68	23	41
63	0	0	1	112
64	1	9	37	80
65	0	11	8	120
66	0	0	0	121
67	0	0	3	101
68	0	0	112	90
69	0	0	109	10
70	0	1	20	90
71	0	0	18	95
72	0	1	11	104
73	0	0	66	47
74	6	10	88	51
75	0	0	20	84
76	0	2	0	116
77	0	1	70	35
78	3	88	0	43
79	0	3	39	60
80	0	3	43	71
81	0	0	112	7
82	0	0	116	4
83	2	31	57	33
84	16	0	0	70
85	15	77	2	16
86	19	92	59	14
87	2	121	10	14
88	1	82	5	23
89	1	81	20	14
90	0	29	59	45

SAMPLE NO.	THULE	PALEO	ARCH	LOCAL
91	0	61	19	51
92	4	88	25	5
93	0	120	0	0
94	0	68	49	1
95	0	180	2	16
96	0	84	12	21

APPENDIX B

Tills grouped according to stone lithology

Samples have been divided into 5 groups (A to E) based on the similarity of their classes (A - absent, VL - very low, L - low, M - moderate, H - high, and VH - very high). Thule and Paleo were given priority in the classification since they are better indicators of former glacial flow than Arch and Local. The characteristics of the groups are as follows:

Group A - Thule L; Paleo, Arch and Local variable;

Group B - Thule VL; Paleo, Arch and Local variable;

Group C - Thule A; Paleo L to H; Arch and Local variable;

Group D - Thule A; Paleo VL to L; Arch and Local variable;

Group E - Thule A; Paleo A; Arch and Local variable.

Group A				
Sample Number	Amount Thule	Amount Paleo	Amount Arch	Amount Local
84	L	A	A	H
2	L	A	M	A
1	L	A	H	A
74	L	L	H	M
29	L	L	H	M
30	L	L	M	M
26	L	M	M	M
25	L	M	VH	M
35	L	M	M	VL
38	L	M	M	M
32	L	M	L	VL
60	L	M	L	M
62	L	H	L	M
86	L	H	H	L
85	L	H	VL	L

APPENDIX B

Group B				
Sample Number	Amount Thule	Amount Paleo	Amount Arch	Amount Local
57	VL	M	VL	H
51	VL	M	L	H
34	VL	VL	M	H
64	VL	L	M	H
28	VL	L	M	M
36	VL	M	H	M
83	VL	M	H	M
27	VL	A	H	VH
50	VL	L	VL	VH
56	VL	L	L	VH
37	VL	VL	L	VH
41	VL	L	VH	A
43	VL	M	VH	A
39	VL	H	M	A
78	VL	H	A	M
46	VL	H	VL	L
19	VL	H	A	L
88	VL	H	VL	L
87	VL	H	VL	L
89	VL	H	L	L
92	VL	H	L	VL

Group C				
Sample Number	Amount Thule	Amount Paleo	Amount Arch	Amount Local
47	A	L	VH	A
21	A	L	H	M
65	A	L	VL	VH
45	A	M	L	VH
4	A	M	H	H
3	A	M	H	L
90	A	M	H	M
91	A	M	L	M
18	A	H	L	L
93	A	H	A	A
95	A	H	VL	L
96	A	H	VL	L
94	A	H	M	VL

APPENDIX B

Group D				
Sample Number	Amount Thule	Amount Paleo	Amount Arch	Amount Local
72	A	VL	VL	VH
76	A	VL	A	VH
23	A	VL	VL	VH
31	A	VL	L	VH
22	A	VL	L	H
70	A	VL	L	H
53	A	VL	M	H
80	A	VL	M	H
79	A	VL	M	H
61	A	VL	H	H
5	A	VL	H	L
77	A	VL	H	M
16	A	VL	VH	M
48	A	VL	VH	A
20	A	VL	VH	A
49	A	L	VH	A
40	A	L	VH	A

APPENDIX B

Group E				
Sample Number	Amount RBay	Amount Paleo	Amount Arch	Amount Local
33	A	A	A	VH
66	A	A	A	VH
8	A	A	A	VH
63	A	A	VL	VH
55	A	A	VL	VH
12	A	A	VL	VH
67	A	A	VL	VH
58	A	A	VL	VH
75	A	A	L	H
24	A	A	L	H
9	A	A	L	L
71	A	A	L	VH
6	A	A	M	VH
7	A	A	H	H
15	A	A	M	H
11	A	A	M	M
73	A	A	H	M
59	A	A	H	M
42	A	A	H	M
52	A	A	H	M
81	A	A	VH	VL
82	A	A	VH	VL
17	A	A	VH	A
44	A	A	VH	A
14	A	A	VH	A
69	A	A	VH	L
13	A	A	VH	L
10	A	A	VH	L
54	A	A	VH	M
68	A	A	VH	H

APPENDIX C

Granulometry of tills

SAMPLE NO.	SAND (%)	SILT (%)	CLAY(%)
1	71.85	16.66	11.49
2	84.06	9.73	6.21
3	52.32	30.05	17.63
4	74.16	18.59	7.25
5	71.8	20.27	7.93
6	78.57	16.62	4.81
7	94.91	3.43	1.66
8	86.97	10.03	3
9	84.23	14.95	0.82
10	79.082	18.227	2.6911
11	62.81	31.79	5.4
12	63.13	31.6	5.27
13	65.83	25.6	8.57
14	79.44	15.52	5.04
15	77.05	15.79	7.16
16	73.18	17.96	8.86
17	72.58	17.8	9.62
18	71.62	16.91	11.47
19	82.58	10.17	7.25
20	63.351	22.703	13.946
21	64.58	29.88	5.54
22	79.47	17.99	2.54
23	81.56	15.67	2.77
24	64.87	26.29	8.84
25	63.66	24.94	11.4
26	76.17	21.48	2.35
27	78.11	16.22	5.67
28	61.37	23.32	15.31
29	63.19	25.87	10.94
30	92.06	6.03	1.91
31	65.21	22.12	12.67
32	76.23	21.93	1.84
33	43.067	34.744	22.189
34	70.54	18.79	10.67
35	62.9	22.96	14.14
36	69.44	19.84	10.72
37	55.44	25.98	18.58
38	70.3	21.32	8.38
39	76.46	14.5	9.04
40	55.42	32.07	12.51
41	79.59	15.48	4.93
42	63.15	22.59	14.26

SAMPLE NO.	SAND (%)	SILT (%)	CLAY(%)
43	79.62	14.28	6.1
44	62.73	19.1	18.17
45	63.57	23.63	12.8
46	87.13	8.3	4.57
47	68.05	22.74	9.21
48	65.71	26.56	7.73
49	65.23	24.03	10.74
50	67.86	23.12	9.02
51	66.93	25.04	8.03
52	55.27	27.54	17.19
53	81.16	16.63	2.21
54	97.38	1.17	1.45
55	53.26	30.39	16.35
56	57.54	27.76	14.7
57	86.4	12.13	1.47
58	82.91	12.75	4.34
59	68.12	25.84	6.04
60	79.43	16.78	3.79
61	66.65	19.74	13.61
62	60.16	29.3	10.54
63	57.784	23.868	18.348
64	70.54	19.19	10.27
65	75.81	15.63	8.56
66	62.15	23.4	14.45
67	88.55	9.42	2.03
68	62.4	27.37	10.23
69	96.46	1.65	1.89
70	61.68	30.14	8.18
71	75.53	21.12	3.35
72	83.6	13.58	2.82
73	94.67	3.36	1.97
74	86.3	11.06	2.64
75	74.67	21.96	3.37
76	50.93	27.71	21.36
77	76.69	8.43	14.88
78	70.36	27.07	2.57
79	54.75	33.08	12.17
80	80.67	15.33	4
81	83.22	15.15	1.63
82	76.69	8.43	14.88
83	77.05	15.79	7.16
84	72.39	16.74	10.87
85	89.1	7.18	3.72
86	71.64	19.34	9.02
87	89.02	8.05	2.93
88	72.53	21.13	6.34
89	80.2	11.44	8.36
90	67.09	23.5	9.41

SAMPLE NO.	SAND (%)	SILT (%)	CLAY(%)
91	90.09	6.68	3.23
92	55.21	34.25	10.54
93	56.82	30.33	12.85
94	75.21	19.58	5.21
95	67.9	26.35	5.75

APPPENDIX D

Geochemistry of tills

SAMPLE NO.	CO(ppm)	CR(ppm)	CU(ppm)	FE(%)	MN(ppm)	MO(ppm)
1	21	99	67	6.0	399	1
2	22	115	123	6.2	1670	1
3	19	70	54	4.4	380	2
4	31	74	147	4.4	980	2
5	28	97	84	4.8	353	1
6	20	82	156	5.2	880	4
7	44	115	140	6.4	1400	6
8	27	64	80	5.9	1700	4
9	21	55	112	2.8	243	3
10	15	82	72	5.0	980	4
11	34	115	72	6.3	810	4
13	32	120	130	5.0	600	2
14	24	124	151	7.3	1000	6
15	18	100	120	8.4	1200	7
16	17	96	60	5.9	1270	1
17	21	146	108	6.0	420	4
18	15	84	60	5.4	920	1
19	12	86	88	6.0	2000	1
20	31	98	92	6.6	761	1
21	37	100	146	6.0	700	2
22	28	61	59	6.2	1180	2
23	29	60	62	4.9	1500	2
24	18	88	75	6.6	1887	1
25	29	120	150	5.9	620	2
26	32	107	155	6.9	580	2
27	24	65	57	4.1	590	3
28	34	113	129	7.1	824	1
29	26	119	189	8.1	455	2
30	15	73	86	5.9	510	2
31	29	65	64	6.1	1250	4
32	21	98	81	5.8	374	1
33	19	65	73	5.9	900	1
34	11	80	57	5.2	330	2
35	27	122	115	6.1	520	1
36	26	93	66	5.1	480	2
37	19	84	92	5.8	1150	1
38	11	84	51	4.7	340	1
39	21	75	37	3.7	380	3
40	19	79	70	5.5	394	1
41	18	100	90	6.7	560	3
42	22	70	104	6.3	1100	6
43	22	85	60	4.9	407	1
44	4	62	146	2.0	148	12
45	12	67	51	5.0	440	2

SAMPLE NO.	CO(ppm)	CR(ppm)	CU(ppm)	FE(%)	MN(ppm)	MO(ppm)
46	11	76	69	4.6	290	2
47	49	86	161	7.3	885	1
48	21	84	74	5.1	1409	1
49	31	74	65	5.1	490	1
50	21	57	47	4.5	470	1
51	15	78	68	5.6	1200	1
52	45	102	102	5.9	900	3
53	30	72	245	7.5	487	1
54	30	74	184	6.7	1300	3
55	24	54	68	5.8	1240	4
56	14	78	68	6.4	970	1
57	11	82	64	4.9	430	1
58	22	60	37	6.1	1180	1
59	36	124	194	7.1	1545	1
60	16	84	50	6.0	1500	16
61	20	122	156	8.0	1175	3
62	21	46	880	5.3	520	3
63	32	85	72	8.0	850	1
64	31	190	143	9.1	640	14
65	77	76	1905	12.2	237	15
66	21	82	173	13.6	467	1
67	30	140	275	17.8	310	4
68	50	86	206	7.3	1010	3
69	17	124	61	7.4	1100	2
70	19	58	52	8.1	1650	3
71	15	66	42	5.6	1000	2
72	31	48	88	4.7	1210	4
73	34	65	161	4.5	1215	4
74	47	106	112	7.2	3300	3
75	35	80	143	7.4	1015	1
76	21	88	162	4.6	740	1
77	36	137	152	6.7	370	2
78	9	58	28	3.3	365	1
79	16	42	66	2.8	420	1
80	21	56	69	4.0	490	3
81	39	104	48	6.0	1360	1
82	33	116	87	7.0	1300	3
83	9	58	28	3.3	365	1
84	17	96	60	5.9	1270	1
85	34	78	103	5.7	940	1
86	45	86	103	7.4	1960	2
87	23	109	62	6.3	484	1
88	29	64	82	4.8	1620	3
89	35	88	117	8.0	1240	3
90	21	118	140	9.2	960	7
91	9	72	80	3.4	250	2
92	26	112	142	4.8	780	3
93	11	68	24	3.8	780	2
94	3	27	24	0.9	200	3
95	10	30	27	1.7	320	5
96	24	56	114	3.9	405	3

APPENDIX E

Munsell Colours

MUNSELL CODE - DESCRIPTION	GROUP	SITE
10YR3/2 = VERY DARK GREYISH BROWN	GREY/BROWN	7
10YR4/1 = DARK GREY	GREY	3
10YR4/2 = DARK GREYISH BROWN	GREY/BROWN	27
10YR4/2		86
10YR5/3 = BROWN	BROWN	16
10YR5/3		19
10YR5/3		23
10YR5/3		35
10YR5/3		84
10YR5/3		89
10YR5/4 = YELLOWISH BROWN	BROWN	15
10YR5/4		70
10YR5/4		90
10YR6/1 = GREY	GREY	9
10YR6/1		76
10YR6/1		79
10YR6/1		94
10YR6/2 = LIGHT BROWNISH GREY	GREY/BROWN	24
10YR6/2		45
10YR6/2		56
10YR6/3 = PALE BROWN	BROWN	25
10YR6/3		64
10YR6/3		71
10YR6/3		81
10YR7/1 = LIGHT GREY	GREY	91
10YR7/1		95
2.5Y4/2 = DARK GREYISH BROWN	GREY/BROWN	21
2.5Y4/2		72
2.5Y4/2		74
2.5Y5/2 = GREYISH BROWN	GREY/BROWN	6
2.5Y5/2		10
2.5Y5/2		11
2.5Y5/2		18
2.5Y5/2		30
2.5Y5/2		36
2.5Y5/2		37
2.5Y5/2		38
2.5Y5/2		42
2.5Y5/2		51
2.5Y5/2		57

MUNSELL CODE - DESCRIPTION	GROUP	SITE
2.5Y5/2= GREYISH BROWN	GREY/BROWN	60
2.5Y5/2		62
2.5Y5/2		92
2.5Y6/2 = LIGHT BROWNISH GREY	GREY/BROWN	4
2.5Y6/2		14
2.5Y6/2		22
2.5Y6/2		26
2.5Y6/2		29
2.5Y6/2		34
2.5Y6/2		39
2.5Y6/2		46
2.5Y6/2		50
2.5Y6/2		54
2.5Y6/2		58
2.5Y6/2		61
2.5Y6/2		69
2.5Y6/2		82
2.5Y7/2 = LIGHT GREY	GREY	17
2.5Y7/2		93
2.5Y7/2		96
2.5YR4/2 = WEAK RED	WEAK-RED	78
2.5YR4/2		83
2.5YR5/2 = WEAK RED	WEAK-RED	8
5Y5/2 = OLIVE GREY	GREY	52
5Y6/1 = GREY	GREY	13
5Y6/1		41
5Y6/1		49
5Y6/1		80
5Y6/2 = LIGHT OLIVE GREY	GREY	77
5Y6/3 = PALE OLIVE	PALE-OLIVE	73
5YR5/3 = REDDISH BROWN	BROWN	85
7.5YR4/4 = BROWN	BROWN	31
7.5YR5/4 = BROWN	BROWN	55
7.5YR5/6 = STRONG BROWN	BROWN	44
7.5YR6/4 = LIGHT BROWN	BROWN	88
7.5YR6/6 = REDDISH YELLOW	REDDISH-YELLOW	67

APPENDIX F

Factor analysis applied to stone count data

The software used to perform the factor analysis was STAT-ITCF. For statistical purposes, the sample sites (the individuals) can be viewed as statistical populations with a number of attributes (variables). In this case, the variables consist of the lithological components of the stone counts - Thule, Paleo, etc. - divided into 18 classes (listed in Table 4.1) and the location of the 96 sites (in relative x and y co-ordinates). The relationship between lithological variables may reveal the presence of distinct tills and, together with the spatial variables, the directions of former glacial flows can be inferred.

The raw data is first centred and reduced, which compensates for the fact that different numbers of stones were collected at each site. The variables and the sites are then projected into the space confined by a five-dimensional hypersphere with factor axes FAX1 to FAX5. The location of the variables inside the hypersphere can be expressed as a co-ordinate which is a function of each factor axis and the distance from the center of the sphere to that point. In addition, each variable has a relative weight which is used in the construction of a cloud of points. To determine which of the variables weigh heavily in the construction of the axis, the mean weight is calculated. Variables with values greater than the mean value are considered to have greater importance.

Planes constructed using any 2 orthogonal factor axes are used as surfaces onto which the points of the cloud (the five-dimensional representation of the statistical population) are projected. From these planes, clusters of the important variables and associated sites can be identified. The five planes constructed from the various factor axes yield 7 combinations of variables:

Group I (FAX2 vs. FAX3): Paleo(H), Thule(VL), Local(L), Arch(VL);

Group II (FAX2 vs. FAX1): Arch(H), Paleo(M), Local(M), Thule(L);

Group III (FAX2 vs. FAX1): Arch(VH), Paleo(A), Thule(A);

Group IV (FAX2 vs. FAX4): Arch(VH), Arch(H), Thule(A), Paleo(A), Local(M);

Group V (FAX1 vs, FAX3): Local(VH), Local(H), Paleo(VL), Arch(VL);

Group VI (FAX3 vs. FAX4): Arch(H), Local(M), Paleo(A);

Group VII (FAX3 vs. FAX4): Local(H), Arch(M), Paleo(VL).

The geographic distributions of the sites belonging to these groups are as follows:

Group I: high in Paleo and Thule, and low in Arch and Local, Group I is composed of relatively few points (12). However, the dispersal pattern of these points is illuminating when considered together with the bedrock geology. Thule and Paleozoic rocks outcrop on the south side of Bache Peninsula, so understandably nearby sites (78, 85, 86, 87, 88, 89, 95 and 96) have high concentrations of these lithologies. Group I sites to the south, on Cocked Hat and Brevoort islands (sites 62 and 46), indicate southward glacial transport of Paleo and Thule from their bedrock source. The remaining two Group I sites are located on Wade Point (18, 19). Although deposition of Thule erratics by southward flowing ice should be considered, a more likely source for the erratics is a small outcrop of Thule located approximately seven kilometres to the west of the sites, between Alfred Newton and MacMillan glaciers.

Group II: also high in both Paleo and Thule, but moderate in Local and high in Arch, the sites for this group are more numerous and more widely distributed than Group I. Again, sites high in Paleo and Thule are to be expected in the north in close proximity to where Paleozoic and Thule rocks outcrop (sites 83, 90 and 91 on Bache Peninsula; site 77 on Thorvald Peninsula; and sites 73 and 74 in Alexandra Fiord), but numerous sites with the same concentrations are also found to the south. Three sites (51, 60, 64) on Pim Island and all 9 sites on Cape Herschel are included in this group. From the raw data, sites 11 (Baird Inlet), 42, 52 and 59 (Leffert Glacier) contain no Thule or Paleo rocks but are controlled by the weight of Arch and Local variables. The remaining sites - 1 (Stanfield Point), 3 and 4 (Cape Isabella), 36 (just west of Cape Herschel Peninsula) and 43 (Leffert Glacier) are all very close to present-day glaciers, indicating that Paleo and Thule erratics at these sites could have their sources under the ice cap. From the general distribution of Group I sites, it can be noted that sites in the westernmost interior of the the fiords (Flagler Bay, Hayes Fiord, Alexandra Fiord and Baird Inlet) are not included. Therefore, Group II is indicative of north - south flow.

Group III: zero Paleo and Thule but high in Arch, Group III sites are found in the westernmost interior of Hayes Fiord (79, 80, 81, 82), Alexandra Fiord (88) and Baird Inlet (6, 7, 10, 13, 14, 15). None of the sites on Cape Herschel are included in this group and only one site (61) on Pim Island. The general distribution indicates a component of west to east former flow out of the fiords, at the heads of which glaciers exist today. The eastern coastal sites included in this group (16, 17, 20, 22, 24, 31, 40, 44, 47, 48, 49, 53, 54), also indicate west to east flow (in the same direction nearby glaciers are advancing today) since they have no component of Paleo or Thule which have their sources to the north.

Group IV: Group IV is similar to Group III - high in Arch, moderate in Local and zero in Thule and Paleo. These sites are found in the westernmost interior of Hayes Fiord (81, 82), Alexandra Fiord (73, 74), almost all sites in Baird Inlet (6, 7, 8, 10, 11, 12, 13, 14) and one of two sites in Cadagon Inlet (1). The distribution of these sites within the fiords reaffirms the existence of a west to east component of former flow out of the fiords. As for Group III, numerous other sites on Johan Peninsula are also included in Group IV. In the critical area of Cape Herschel - Pim Island, only 3 sites belong to Group IV (21, 25, 29).

Groups V and VI: both groups are widely distributed throughout the study area. They are without significance in determining the former direction of glacial flow because of the strong component that is locally derived. It can also be noted that Group V has a small component of Paleo which is absent altogether in Group VI. The large component of locally derived material is perhaps indicative of frost shattering on Archean bedrock, although locally derived material could unavoidably be mistaken for glacially transported material. These groups are not significant since all areas are susceptible to this phenomenon.

Group VII: These sites are found in Hayes Fiord (79, 80), on northern Johan Peninsula (70, 75), on Pim Island (51, 57, 61, 64), west of Rice Strait (53), west of Cape Herschel (22, 24, 31, 34, 37) and north of Baird Inlet (15). Low in Paleo, moderate in Arch and high in Local, this group possibly indicates a mixing of a frost shattered component and debris derived from north-south and east-west flows.

The distribution of sites in groups III and IV, indicating west to east flow out of the fiords at some earlier time when the glaciers at the heads of these fiords were more expansive, is to be expected. The most significant groups are I and II, which indicate former north to south flow.